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Inverter Based DGs for Power Quality Enhancement and Protection in Distribution Network

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Abstract--In this paper, a new three-phase wind energy inverter (WEI) with flexible AC transmission system (FACTS) capability is presented. The proposed inverter is placed between the wind turbine and the grid, same as a regular WEI, and is able to regulate reactive power transferred to the grid. The goal of this paper is to introduce new ways to increase the penetration of renewable energy systems into the distribution systems. This will encourage the utilities and customers to act not only as a consumer, but also as a supplier of energy. Moreover, using the new types of converters with FACTS capabilities will significantly reduce the total cost of the renewable energy application. In this paper, modular multilevel converter is used as the desired topology to meet all the requirements of a three-phase system such as efficiency, and total cost of the system. The simulations for an 13-level inverter have been done in MATLAB/Simulink.

Keywords: Modular multilevel converter (MMC), Distributed Generation (DG), Voltage-Source Inverters (VSIs).

1. Introduction

The increasing prevalence of distributed generators (DGs) has raised serious concerns about the impact of such units on the operation of distribution systems. One of the most critical challenges is related to fault conditions, during which DGs as well as the grid contribute to the fault current, with the result that, when DGs are connected to the system, the fault current detected by the protective devices is greater than the original fault current without the DGs. This increase in the level of the fault current identified by the protective devices may result in the malfunction or miscoordination of the protective devices [1]–[3].

A variety of solutions have been offered as a means of eliminating the effects of DGs on fault currents. IEEE Standard 1547 [4] requires DGs to be disconnected from the power system at the moment of fault detection. Such a response, however, decreases the reliability of the system and may cause synchronization problems when the DGs are reconnected.

Some researchers have proposed a DG capacity threshold in order to avoid the modification of the protection system [5]–[7]. The literature contains suggestions for determining the optimal location of the DGs as a way of reducing their effect on the operation of the protective devices [7], [8]. Although these solutions may work well technically, the requirements associated with the protection system entail size and location restrictions with respect to the connection of the DGs.

The study of fault current characteristics of the IBDGs requires a comprehensive reevaluation of various protection design aspects. A voltage-source inverter (VSI) typically has a dc-link capacitor that is sized to decouple the prime-mover dynamics from those of the network. Accordingly, the effect of the prime-mover itself on fault current can be neglected, and only the dynamics of the inverter with its associated controller(s) are considered [9]. Moreover, the IBDGs have their own internal protection to ensure safety of semiconductor devices against large over currents flowing through them [10]. Usually, this current is in the range of two to three times of the rated load current [11], [12]. The effect of such an internal protection needs to be considered in the overall network protection scheme since the inverter internal protection cannot detect fault currents with levels lower than its settings.

There are principally two types of control schemes that generally govern IBDGs, viz., voltage control and current control [9]. This paper conducts a detailed investigation of network protection schemes for a typical industrial and commercial power distribution system, shown in Fig. 1, containing IBDGs with both control types. In addition, it also includes a comprehensive analysis of the fault current contributions of various DGs, as well as the impact of changes in inverter control between the current control mode and the voltage control mode on the associated feeder protection.

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The effect of the IBDG controller on protection was earlier studied in [13]–[17]. The authors in [13]–[15] proposed adding fault current limiters in series with feeders containing DGs in order to limit the current contribution fed from them. Adaptive relaying algorithms were proposed in [16] and [17] to solve the detection problems of the IBDGs. In [18], the authors studied the effect on fuse saving schemes, whereas in [3], the authors introduced a flywheel energy storage system in parallel with the DG. While these schemes showed promising results, they are expensive solutions requiring extra equipment to be installed in the network. Furthermore, all of the aforementioned publications [13]–[18] did not investigate the effects on protection scheme caused by different types of controllers employed in IBDGs. On the other hand, in the few papers that considered the effect of inverter controllers (viz., [19] and [20]), the authors provided solutions that are limited in scope of application. In this paper, a comprehensive analysis was conducted to investigate the differences between the voltage and current control modes for IBDGs' fault characteristics, and a novel protection scheme for the distribution network was proposed. In particular, an adaptive relaying algorithm has been designed to protect the distribution network shown in Fig. 1 from fault contributions of IBDGs that can change their operational mode from current control to voltage control or vice versa.

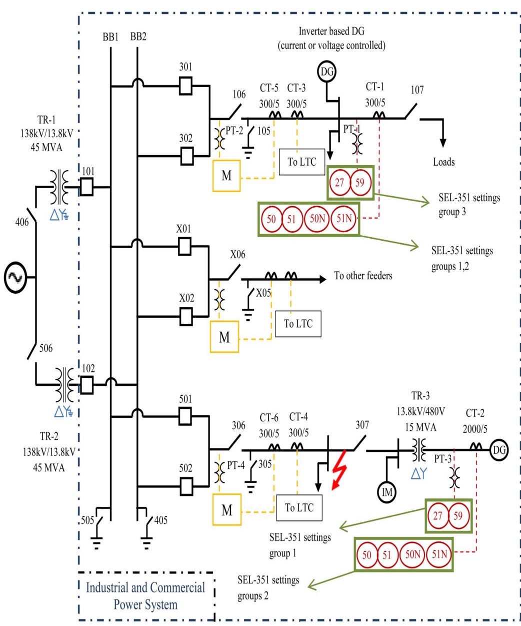

Fig. 1 One-line diagram of a typical industrial and commercial power system distribution network with IBDG installations

2. Current and Voltage Controlled IBDGs

Many commercial DGs utilize a three-phase VSI based on pulse width modulation (PWM) as the utility/load interface. The controls of these IBDGs enable them to meet the wide-ranging demands of their integration with the existing distribution network. The advances made in the control of applications like uninterruptible power supplies (UPS) and ac motor drives gave impetus to the design of controllers for IBDGs. For all practical purposes, there are chiefly two types of control schemes for regulation of the inverter output [19] a voltage controller that will enable it to produce a three-phase ac voltage and a current controller that will force the current supplied to follow a reference signal that is locked in phase with the grid voltage by means of a phase-locked loop.

Current controllers for VSIs have become attractive in various power electronic applications including UPS, active power filters, ac motor drives, high power factor ac/dc converters, and grid-connected inverters [21]. The current controller type and structure can be precisely tailored for each application as it plays a significant role in the performance of the converter as well as the power quality of its output. Many types of current controllers were suggested in the literature for various applications [21], [22]. However, current-controlled DGs suffer from the major disadvantage of inability to independently maintain their terminal voltage to the distribution network levels.
They rely on the utility grid or other voltage-controlled DGs for maintenance of voltage, and in the absence of such a voltage support, the current-controlled DG terminal becomes vulnerable to under voltage faults. On the other hand, voltage controllers have also been applied for VSIs in applications such as parallel-connected stand-alone inverters [23] and plug and-play operation of micro grids [24]. IBDGs under voltage control mode have become indispensable as they help in regulating the voltage of micro grid especially during the islanded conditions. IBDGs operating in voltage control mode are unable to precisely regulate their output current, and these are therefore highly susceptible to over current faults upon a short circuit.

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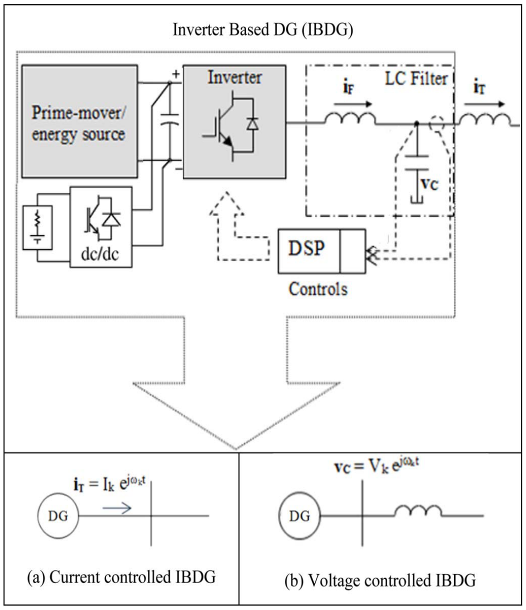

Fig. 2 Conditional analogy of an IBDG, based on the employed control scheme, to (a) current source or (b) voltage source.

Fig. 2 illustrates the conditional analogy of an IBDG to a current source or voltage source that is dependent upon the employed control scheme-whether it is operated in the current control mode or voltage control mode. The generic block diagrams of both current-controlled and voltage-controlled inverters in DG applications are illustrated in Fig. 3(a) and (b), respectively. These controllers are generally implemented in a digital signal processor. It is to be noted that the purpose of the protection analysis carried out in this paper is to highlight the key problems caused by a broad range of commercially available DGs used in industrial power systems. Therefore, Figs. 2 and 3 contain only representative block diagrams even though numerous variations are known to exist in the exact methods of controller implementation (as noted in the literature [21]–[24]).

Multifunction inverters are also commercially available from various manufacturers like SatCon, SMA, Xantrex, etc. They are generally installed in industrial sites where uninterrupted operation is desired in both grid-connected and stand-alone (islanded) conditions. Such IBDGs are frequently used with renewable sources like solar/PV and wind power together with energy storage. For instance, SatCon Technology Corporation manufactures inverter products from low kilowatt to megawatt ratings with functionalities that include stand-alone and grid connected modes, synchronization, power factor correction, and utility outage ride-through. The operation of these inverters is known to transition between the current control mode and the voltage control mode based on system requirements and the state of interconnection [25], [26]. The protection schemes at industrial sites employing such DGs need special attention, and a detailed investigation is carried out in the following section.

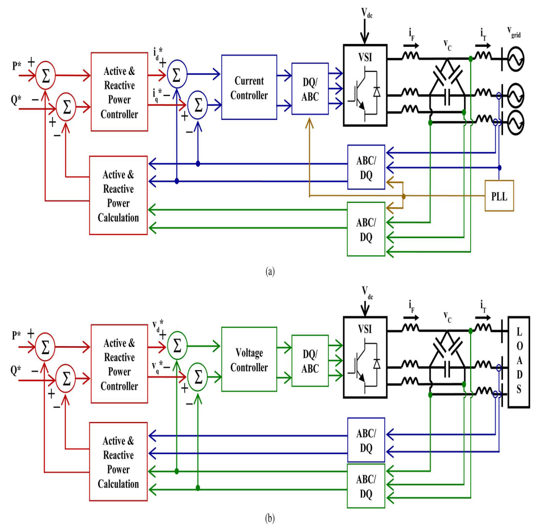

Fig. 3 Generic block diagrams illustrating the operation of IBDGs during (a) current control and (b) voltage control modes.

3. Proposed configuration of MMC for DG:

MMC has gained increasing attention recently. A number of papers were published on the structure, control, and application of this topology [27], [28], but none has suggested the use of that for inverter + D-STATCOM application. This topology consists of several half-bridge (HB) sub modules (SMs) per each phase, which are connected in series. An *n*-level single phase MMC consists of a series connection of $2(n-1)$ basic SMs and two buffer inductors. Each SM possesses two semiconductor switches, which operate in complementary mode, and one capacitor. The exclusive structure of MMC becomes it an ideal candidate for medium-to-high-voltage applications such as wind energy applications. Moreover, this topology needs only one dc source, which is a key point for wind applications. MMC requires large capacitors which may increase the cost of the systems; however, this problem is offset by the lack of need for any snubber circuit.

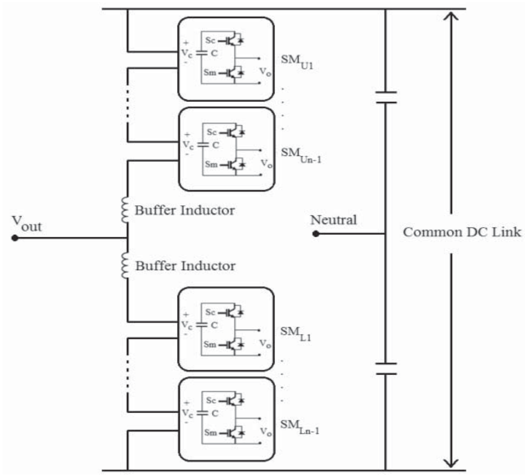

Fig. 4 Structure of a single-phase MMC inverter structure

The main benefits of the MMC topology are: modular design based on identical converter cells, simple voltage scaling by a series connection of cells, simple realization of redundancy, and possibility of a common dc bus. Fig. 4 shows the circuit configuration of a single-phase MMC and the structure of its SMs consisting of two power switches and a floating capacitor.

The output voltage of each SM (v_o) is either equal to its capacitor voltage (v_C) or zero, depending on the switching states. The buffer inductors must provide current control in each phase arm and limit the fault currents. To describe the operation of MMC, each SM can be considered as a two pole switch. If S_{ui}, which is defined as the status of the ith sub module in the upper arm, is equal to unity, then the output of the i_{th} SM is equal to the corresponding capacitor voltage; otherwise it is zero. Likewise, if S_{li} which is defined as the status of the i th sub module in the lower arm, is equal to unity, then the output of the i th lower SM is equal to the corresponding capacitor voltage; otherwise it is zero.

Generally, when S_{ui} or S_{li} is equal to unity, the ith upper or lower SM is ON; otherwise it is OFF. Therefore, the upper and lower arm voltages of the MMC are as follows:

$$v_{\text{upperArm}} = \sum_{i=1}^{n-1} (S_{\text{ui}} v_{\text{ci}}) + v_{11} \quad (1)$$

$$v_{\text{lowerArm}} = \sum_{i=1}^{n-1} (S_{\text{li}} v_{\text{ci}}) + v_{12} \quad (2)$$

where v_{11} and v_{12} are the voltages of the upper and lower buffer inductors, n is the number of voltage levels, and v_{ci} is the voltage of the i th SMs capacitor in upper arm or lower arm. A three-phase 13-levelMMC inverter consists of 20 SMs which translates to 40 power switches, 20 capacitors, and 2 buffer inductors. In this paper we have used 13-level dc-ac converter configuration.

4. Investigation of Current-Controlled and Voltage-Controlled DGs on Distribution Network

In order to examine the effects of current- and voltage controlled IBDGs on a distribution network, they have been modeled in MATLAB/Simulink together with the Thevenin's equivalent for the rest of the system in Fig. 1. Subsequently, a fault was created across the nearby load, and the contribution of the IBDG to fault current was evaluated. The operation parameters for IBDG were as follows: three phase, 50 kW, 60 Hz, 480 Vac (line-line), and IGBT-based VSI-PWM inverter operating at 3.6-kHz switching frequency with a 750-V dc bus.

The most critical issue to control MMC is to maintain the voltage balance across all the capacitors. Therefore, the SMs' voltages are measured and sorted in descending order during each cycle. If the current flowing through the switches is positive, so that capacitors are being charged, n upper Arm and n upper Arm and of the SMs in upper arm and lower arm with the lowest voltages are selected, respectively. As a result, ten capacitors with lowest voltages are chosen to be charged. Likewise, if the current flowing through the switches is negative, so that capacitors are being discharged, n upper Arm and n upper Arm of the SMs in upper arm and lower arm with highest voltages are selected, respectively. As a result, twelve capacitors with highest voltages are chosen to be discharged. Consequently, the voltages of the SMs' capacitors are balanced.

The inverter transfers the whole active power of the wind, excluding its losses, to the grid. The amount of reactive power is dictated by the target PF. When the active power from the wind turbine increases, the controller increases the power angle δ in order to output more active power to the grid in order to decrease the dc link voltage. The modulation index m is also increased when the inverter is supposed to inject more reactive power to the grid. The transient response of the PI controllers used to control the modulation index and delta can be adjusted by changing the

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proportional and integral coefficients of the controllers. The practical results show that the performance of the proposed controller strategy is sufficiently close to the simulation results. The PI controllers show a proper performance during severe changes in the wind speed, which is emulated by the wind emulator.

5. SIMULATION RESULTS

The simulation circuit of proposed RSC circuit is shown in Fig.12. The simulation circuit of perturb and observe MPPT method is shown in Fig.13. The simulation circuit of Incremental Conductance MPPT method is shown in Fig.14.

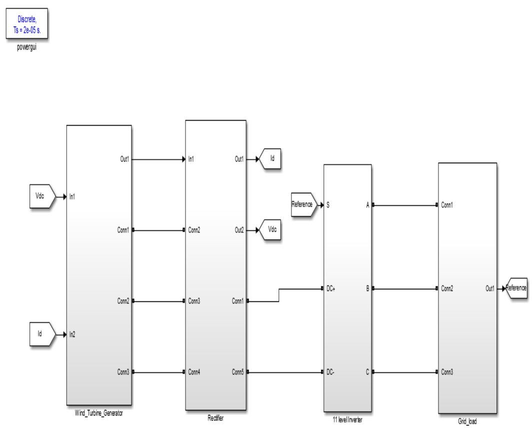

Fig. 5 Simulation Configuration of Inverter based DG

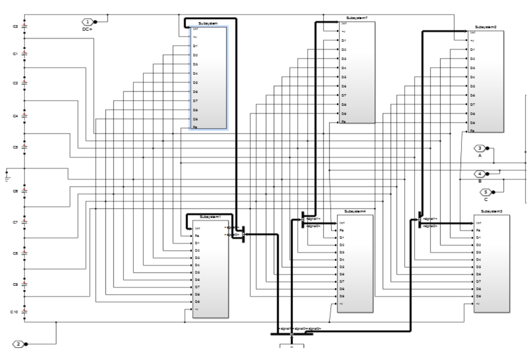

Fig. 6 Simulation Configuration of Proposed 13-level MMC

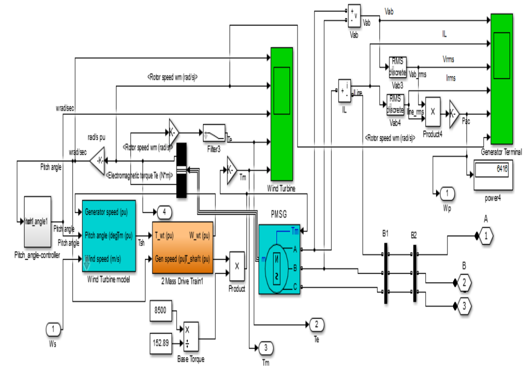

Fig. 7 PMSG based Wind Energy System

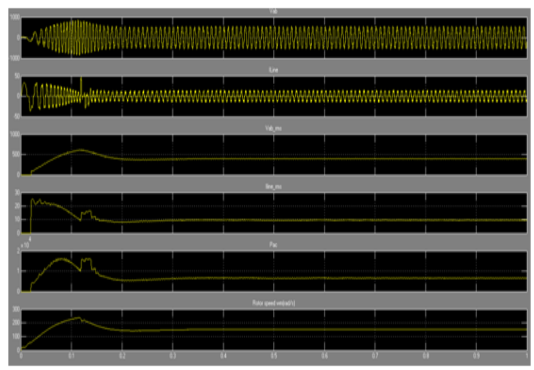

Fig. 8 Wind Energy System Waveforms

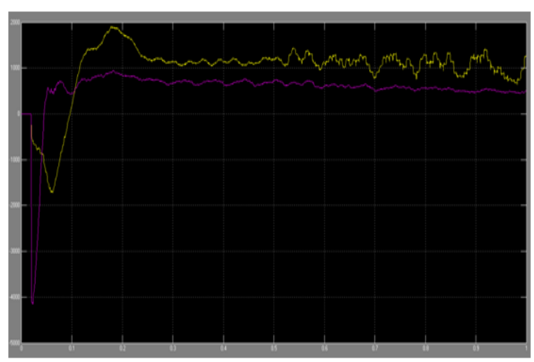

Fig. 9 Active and Reactive Power of the Load

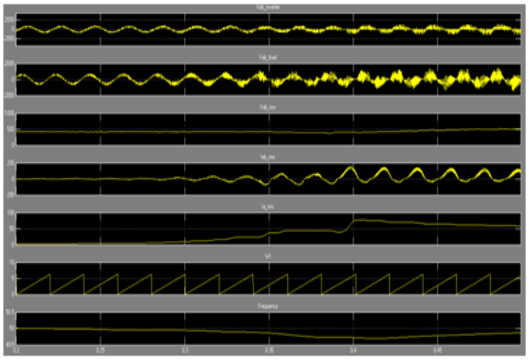

Fig. 10 DG Inverter Output Waveforms

6. CONCLUSION

In this paper, the concept of a new multilevel inverter with FACTS capability for small-to-mid-size wind installations is presented. The proposed system demonstrates the application of a new inverter with FACTS capability in a single unit without any additional cost. Replacing the traditional renewable energy inverters with the proposed inverter will eliminate the need of any external STATCOM devices This shows a new way in which distributed renewable sources can be used to provide control and support in distribution systems. The proposed controller system the reactive power is controllable by the modulation index *m*. The simulation results for an 13-level inverter are presented in MATLAB/Simulink. The proposed system has produced the better performance.

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