A T-Connected Transformer and Three-leg VSC Based DSTATCOM for Power Quality Improvement

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***Abstract*—In this paper, a new three-phase four-wire distribution static compensator (DSTATCOM) based on a T-connected transformer and a three-leg voltage source converter (VSC) is proposed for power quality improvement. The T-connected transformer connection mitigates the neutral current and the three-leg VSC compensates harmonic current, reactive power, and balances the load. Two single-phase transformers are connected in T-configuration for interfacing to a three-phase four-wire power distribution system and the required rating of the VSC is reduced. The insulated gate bipolar transistor (IGBT) based VSC is supported by a capacitor and is controlled for the required compensation of the load current. The dc bus voltage of the VSC is regulated during varying load conditions. The DSTATCOM is tested for power factor correction and voltage regulation along with neutral current compensation, harmonic elimination, and balancing of linear loads as well as nonlinear loads. The performance of the three-phase four-wire DSTATCOM is validated using MATLAB software with its Simulink and power system blockset toolboxes.**

***Index Terms*—Distribution static compensator (DSTATCOM), neutral current compensation, power quality improvement, T-connected transformer, voltage source converter (VSC).**

I. Introduction

THREE-PHASE four-wire distribution systems are facing severe power quality problems such as poor voltage regulation, high reactive power and harmonics current burden, load unbalancing, excessive neutral current, etc. [1]–[5]. Three-phase four-wire distribution systems are used in commercial buildings, office buildings, hospitals, etc. Most of the loads in these locations are nonlinear loads and are mostly unbalanced loads in the distribution system. This creates excessive neutral current both of fundamental and harmonic frequency, and the neutral conductor gets overloaded. The voltage regulation is also poor in the distribution system due to the unplanned expansion and the installation of different types of loads in the existing distribution system. In order to control the power quality problems, many standards are proposed, such as the IEEE-519 standard [6].

There are mitigation techniques for power quality problems in the distribution system and the group of devices is known by the generic name of custom power devices (CPDs) [1]. The distribution static compensator (DSTATCOM) is a shunt-connected CPD capable of compensating power quality problems in the load current. Some of the topologies of DSTATCOM for three-phase four-wire system for the mitigation of neutral current along with power quality compensation in the source current are four-leg voltage source converter (VSC), three single-phase VSCs, three-leg VSC with split capacitors [3], three-leg VSC with zig-zag transformer [7]–[9], and three-leg VSC with neutral terminal at the positive or negative of dc bus [10]. The voltage regulation in the distribution feeder is improved by installing a shunt compensator [11]. There are many control schemes reported in the literature for control of shunt active compensators such as instantaneous reactive power theory, power balance theory, synchronous reference frame theory, symmetrical components based, etc. [12], [13]. The synchronous reference frame theory [12] is used for the control of the proposed DSTATCOM.

In this paper, a new topology of DSTATCOM is proposed for a three-phase four-wire distribution system, which is based on three-leg VSC and a T-connected transformer. The T-connected transformer is used in the three-phase distribution system for different applications [14]–[16]. But the application of T-connected transformer for neutral current compensation is demonstrated for the first time. Moreover, the T-connected transformer is suitably designed for magnetic motive force (mmf) balance. The T-connected transformer mitigates the neutral current and the three-leg VSC compensates the harmonic current and reactive power, and balances the load. The insulated gate bipolar transistor (IGBT) based VSC is self-supported with a dc bus capacitor and is controlled for the required compensation of the load current. The DSTATCOM is designed and simulated using MATLAB software with its Simulink and power system blockset (PSB) toolboxes for power factor correction and voltage regulation along with neutral current compensation, harmonic elimination, and load balancing with linear loads as well as nonlinear loads.

II. System Configuration and Design

Fig. 1(a) shows the single-line diagram of the shunt-connected DSTATCOM-based distribution system. The dc capacitor connected at the dc bus of the converter acts as an energy buffer and establishes a dc voltage for the normal operation of the DSTATCOM system. The DSTATCOM can be operated for reactive power compensation for power factor correction or voltage regulation. Fig. 1(b) shows the phasor diagram for the unity power

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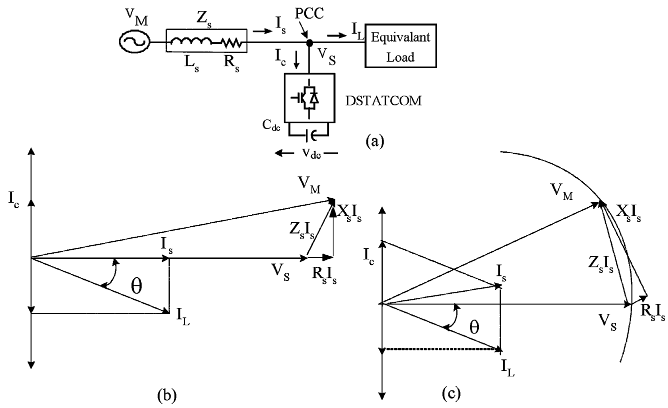

Fig. 1. (a) Single-line diagram of DSTATCOM system. (b) Phasor diagram for UPF operation. (c) ZVR operation.

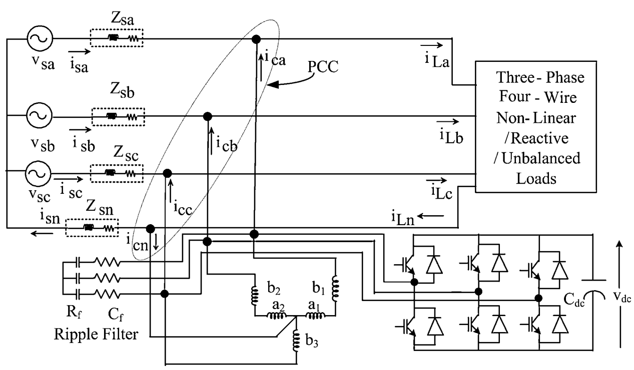

Fig. 2. Schematics of the proposed three-leg VSC with T-connected-transformer-based DSTATCOM connected in distribution system.

factor operation. The DSTATCOM injects a current I_c such that the source current is only I_s, and this is in-phase with voltage. The voltage regulation operation of DSTATCOM is depicted in the phasor diagram of Fig. 1(b). The DSTATCOM injects a current I_c such that the voltage at the load (V_S) is equal to the source voltage (V_M).

The proposed DSTATCOM consisting of a three-leg VSC and a T-connected transformer is shown in Fig. 2, where the T-connected transformer is responsible for neutral current compensation. The windings of the T-connected transformer are designed such that the mmf is balanced properly in the transformer.

A three-leg VSC is used as an active shunt compensator along with a T-connected transformer, as shown in Fig. 2, and this topology has six IGBTs, three ac inductors, and one dc capacitor. The required compensation to be provided by the DSTATCOM decides the rating of the VSC components. The data of DSTATCOM system considered for analysis is shown in the Appendix. The VSC is designed for compensating a reactive power of 12 kvar, as decided from the load details. The selection of interfacing inductor, dc capacitor, and the ripple filter are given in the following sections.

A. DC Capacitor Voltage

The minimum dc bus voltage of VSC of DSTATCOM should be greater than twice the peak of the phase voltage of the system [17]. The dc bus voltage is calculated as

$$V_{\rm dc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}m} \tag{1}$$

where m is the modulation index and is considered as 1, and V_{LL} is the ac line output voltage of DSTATCOM. Thus, $V_{\rm dc}$ is obtained as 677.69 V for V_{LL} of 415 V and is selected as 700 V.

B. DC Bus Capacitor

The value of dc capacitor ($C_{\rm dc}$) of VSC of DSTATCOM depends on the instantaneous energy available to the DSTATCOM during transients [17]. The principle of energy conservation is applied as

$$\frac{1}{2}C_{\rm dc}[(V_{\rm dc}^2) - (V_{\rm dc1}^2)] = 3V\,(aI)\,t \tag{2}$$

where $V_{\rm dc}$ is the reference dc voltage and $V_{\rm dc1}$ is the minimum voltage level of dc bus, a is the overloading factor, V is the phase voltage, I is the phase current, and t is the time by which the dc bus voltage is to be recovered.

Considering the minimum voltage level of the dc bus, $V_{\rm dc1} =$ 690 V, $V_{\rm dc} = 700$ V, $V = 239.60$ V, $I = 27.82$ A, $t = 350$ μs, $a = 1.2$, the calculated value of $C_{\rm dc}$ is 2600 μF and is selected as 3000 μF.

C. AC Inductor

The selection of the ac inductance (L_f) of VSC depends on the current ripple $i_{\rm cr,p\text{-}p}$, switching frequency f_s, dc bus voltage ($V_{\rm dc}$), and L_f is given as [17]

$$L_f = \frac{\sqrt{3}mV_{\rm dc}}{12af_s i_{\rm cr(p\text{-}p)}} \tag{3}$$

where m is the modulation index and a is the overload factor. Considering, $i_{\rm cr,p\text{-}p} = 5\%$, $f_s = 10$ kHz, $m = 1$, $V_{\rm dc} = 700$ V, $a = 1.2$, the L_f value is calculated to be 2.44 mH. A round-off value of L_f of 2.5 mH is selected in this investigation.

D. Ripple Filter

A low-pass first-order filter tuned at half the switching frequency is used to filter the high-frequency noise from the voltage at the PCC. Considering a low impedance of 8.1 Ω for the harmonic voltage at a frequency of 5 kHz, the ripple filter capacitor is designed as $C_f = 5$ μF. A series resistance (R_f) of 5 Ω is included in series with the capacitor (C_f). The impedance is found to be 637 Ω at fundamental frequency, which is sufficiently large, and hence, the ripple filter draws negligible fundamental current.

E. Design of the T-connected Transformer

Fig. 3(a) shows the connection of two single-phase transformers in T-configuration for interfacing with a three-phase