Comprehensive Study of DSTATCOM Configurations

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***Abstract*—In this paper, different Distribution Static Compensators (DSTATCOMs) topologies, state of the art, their performance, design considerations, future developments, and potential applications are investigated for power quality improvement. These DSTATCOMs for three-phase three-wire systems and three-phase four-wire systems are developed and installed in the distribution system for many functions, such as reactive power compensation, harmonics elimination, load balancing, and neutral current compensation. This paper is aimed to explore a broad perspective on DSTATCOMs to researchers, engineers, and the community dealing with the power quality improvement. A classified list of some latest research publications is also provided for quick reference.**

***Index Terms*—Distribution Static Compensator (DSTATCOM), neutral current compensation, power quality, star-delta transformer, star-hexagon transformer, T-connected transformer, voltage source converter (VSC), zig-zag transformer.**

I. Introduction

THREE-PHASE ac power is used unanimously for distribution systems and is used in residential buildings, commercial buildings, office buildings, hospitals, etc. Typical loads in a three-phase distribution system may be computer loads, lighting ballasts, small rating adjustable speeds drives (ASDs) in air conditioners, fans, refrigerators, other domestic and commercial appliances, etc. Almost all these applications use switched-mode power supplies (SMPS), which draw excessive harmonic currents. Three-phase distribution systems are facing severe power quality problems such as poor voltage regulation, high reactive power burden, harmonics current, and load unbalancing. The power quality problems and their mitigation techniques are reported in the literature over the years [1]–[14]. The power quality improvement devices such as three-phase three-wire Distribution Static Compensators (DSTATCOMs) provide reactive power for improving voltage regulation, to eliminate harmonics in the supply currents, and to balance the supply currents when the load currents are unbalanced. There are many standards [15]–[17] proposed to control the quality of electric supply in the distribution system such as IEEE standard 519 [16] and IEEE 1531 [17]. There are surveys and studies on the power quality causes, effects, and analyses [18]–[26]. Many studies and review articles on active shunt compensators for power conditioning are reported in the literature [27]–[50]. The topologies, application, and control of active filters are reported in [46] and [47]. The voltage source type of harmonic loads and their compensation using series active filters is reported by Peng [48]. The power quality improvement in the three-phase three-wire systems using three-phase three-wire shunt active compensators and their topologies, control techniques, field tests, etc., is reported extensively in the literature over the years and the recent publications are listed in [51]–[69].

One of the major problems in three-phase four-wire distribution systems is excessive neutral current along with other power quality problems such as poor voltage regulation, high reactive power burden, harmonics current injection, and load unbalancing [11]–[13]. The excessive neutral current is of both fundamental and harmonics, and the neutral conductor is overloaded resulting in busting of it. The major reason for excessive neutral current in the three-phase four-wire distribution systems is the proliferation of nonlinear loads as well as unbalanced loads. In a survey in the United States, observations on computer power systems have indicated harmonic neutral currents from 0 to 1.73 times the phase current [20]. It has also been revealed that 22.6% of the sites have neutral currents exceeding the full-load phase currents, and this scenario is becoming worst in the recent years due to the proliferation of such nonlinear single-phase loads. The iron-cored inductive ballasts as well as electronic ballasts in fluorescent lighting also contribute to third harmonic currents [20]. The topologies, design, and control techniques for many three-phase four-wire DSTATCOMs for power quality improvement are reported in the literature in recent years [70]–[126]. There are applications of DSTATCOM for aircraft electrical systems [92], wind generation [93], and offshore oil fields [96].

In this paper, various topologies and different control techniques of three-phase three-wire and three-phase four-wire DSTATCOMs are explored for load compensation. The performance of some topologies of three-phase three-wire DSTATCOMs is demonstrated for voltage regulation or power factor correction by reactive power compensation along with harmonics elimination and load balancing. A number of topologies of DSTATCOMs for compensation in three-phase four-wire distribution system are classified, designed, and modeled to simulate their performance for voltage regulation or power factor correction by reactive power compensation along with harmonics elimination, load balancing, and neutral current compensation.

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II. State of the Art

The concept of static compensation is first given by Gyugyi and Strycula in 1976 [51]. A voltage source converter (VSC) with a capacitor at its dc bus is able to inject reactive power of which the quantity of reactive power is limited by the specification of power semiconductor devices. The concept of custom power technology for the distribution system is coined in the literature [13]. Various devices such as DSTATCOM, Dynamic Voltage Restorer (DVR), Unified Power Quality Conditioner (UPQC), etc., are proposed and installed under the name of custom power devices for the enhancement of power quality in distribution systems [13], [14].

The various aspects such as modeling, design, and simulation for reactive power compensation, unbalanced and harmonic compensations, and voltage regulation are reported in [9]–[12]. Monitoring of electric power quality based on different techniques such as wavelet and neural networks is also reported in [10] and [40]. The modeling of the DSTATCOM system [9], [77] is necessary for feasibility and validating the design. The review of the present technology and concept of custom power park is discussed by Ghosh and Ledwich [9]. The voltage regulation function of the DSTATCOM is discussed in [13] and [66]. The concept of constant voltage at point of common coupling (PCC) is realized by pumping extra amount of reactive power into the source side, so that the line drop can be compensated dynamically. The concept of battery energy storage system (BESS) for DSTATCOM is presented [5], [54]. The operation of the DSTATCOM for weak or isolated generation is also important [9]. The DSTATCOM is proposed for compensating voltage quality problems such as sag and swell [8]–[10] and flicker [9]. The reactive power demand in isolated power generation for voltage regulation is achieved using STATCOM [56].

The control schemes of static compensators are developed using the well-known $p-q$ theory proposed by Akagi *et al.* [52]. The extraction of fundamental active and reactive components of currents is demonstrated in this theory. Another widely accepted control theory is synchronous reference frame (SRF) theory reported by Divan *et al.* [53]. This theory is based on the transformation of currents from $a-b-c$ frame to synchronous rotating frame and then extracting the fundamental frequency components. Many other control techniques for shunt compensators have been reported such as sliding mode control [62], voltage template and PI controllers [56], instantaneous symmetrical component theory [9], and neural network theory [61], [65].

III. Topologies of DSTATCOM

The DSTATCOM topologies can be classified based on the number of switching devices, use of transformers for isolation, use of transformers for neutral current compensation, etc. These DSTATCOMs are developed to meet the requirements of different applications such as three-phase three-wire and three-phase four-wire distribution systems.

A. Three-Phase Three-Wire DSTATCOM [51]–[69]

Three-phase three-wire DSTATCOMs are used for the power quality improvement in three-phase three-wire distribution system for the compensation of consumer loads. The topologies for the three-phase three-wire DSTATCOMs are classified as shown in Fig. 1(a). There are nonisolated VSC- and isolated VSC-based DSTATCOMs.

1) Nonisolated VSC-Based DSTATCOMs: Three-leg VSC-based topology is shown in Fig. 1(b) and is widely proposed in the literature [51]–[56]. The topology based on two-leg VSC with split capacitors [12], [60] is advantageous due to the use of less number of switching devices, and this topology is shown in Fig. 1(c). However, the control and regulation of equal dc voltages of dc capacitors and requirement of quite high dc bus voltages are major problems.

2) Isolated VSC-Based DSTATCOMs: Three single-phase VSCs as three-phase three-wire DSTATCOM is reported [12], [64], but the use of more switching devices makes this topology less attractive and this topology is shown in Fig. 1(d). Two other isolated topologies of DSTATCOM using star/delta transformer is shown in Fig. 1(e) and (f). The star/delta transformer is required in this case with kilovolt ampere rating equal to the required reactive power injection. But, the transformer provides isolation from the system and also provides the flexibility to use an "off-the-shelf" VSC for the desired application. However, many other configurations using different transformers may be used in this type of DSTATCOM.

B. Three-Phase Four-Wire DSTATCOM [70]–[126]

Three-phase four-wire DSTATCOMs are used for the power quality improvement in three-phase four-wire distribution systems. The classification of topologies for the three-phase four-wire DSTATCOMs is shown in Fig. 2 and is mainly divided into with transformers- and without transformers-based DSTATCOM topologies.

1) Nonisolated VSC Without Transformers [70]–[86]: The DSTATCOM topologies without transformers are classified as four-leg VSC and three-leg VSC as shown in Fig. 2. The four-leg topology of DSTATCOM is shown in Fig. 3(a) and is widely addressed in the literature [9]–[14], and the fourth leg of VSC is connected to the neutral conductor, so that VSC is controlled for neutral current compensation. The other topologies of DSTATCOM for three-phase four-wire system for the mitigation of neutral current along with power quality compensation in the supply current are three-leg VSC with split capacitors [Fig. 3(b)] [12], three-leg VSC with neutral terminal at the positive or negative of dc bus [Fig. 3(c)] [85], and a hybrid DSTATCOM [Fig. 3(d)] [86].

2) Nonisolated Three-Leg VSC With Transformers [106]–[126]: The DSTATCOM topologies with transformers are classified as nonisolated VSC- and isolated VSC-based DSTATCOMs. A topology of DSTATCOM reported based on nonisolated three-leg VSC with a zig-zag transformer is shown in Fig. 4(a). The application of a zig-zag transformer for the reduction of neutral current is advantageous due to passive compensation, ruggedness, and less complexity over the active compensation techniques [87], [88], [106]–[108]. Another topology based on star/delta transformer and three-leg VSC is shown in Fig. 4(b) [109], [110]. The other transformers such as T-connected transformer [111] and star/hexagon transformer [112] are also used along with three-leg VSC as three-phase

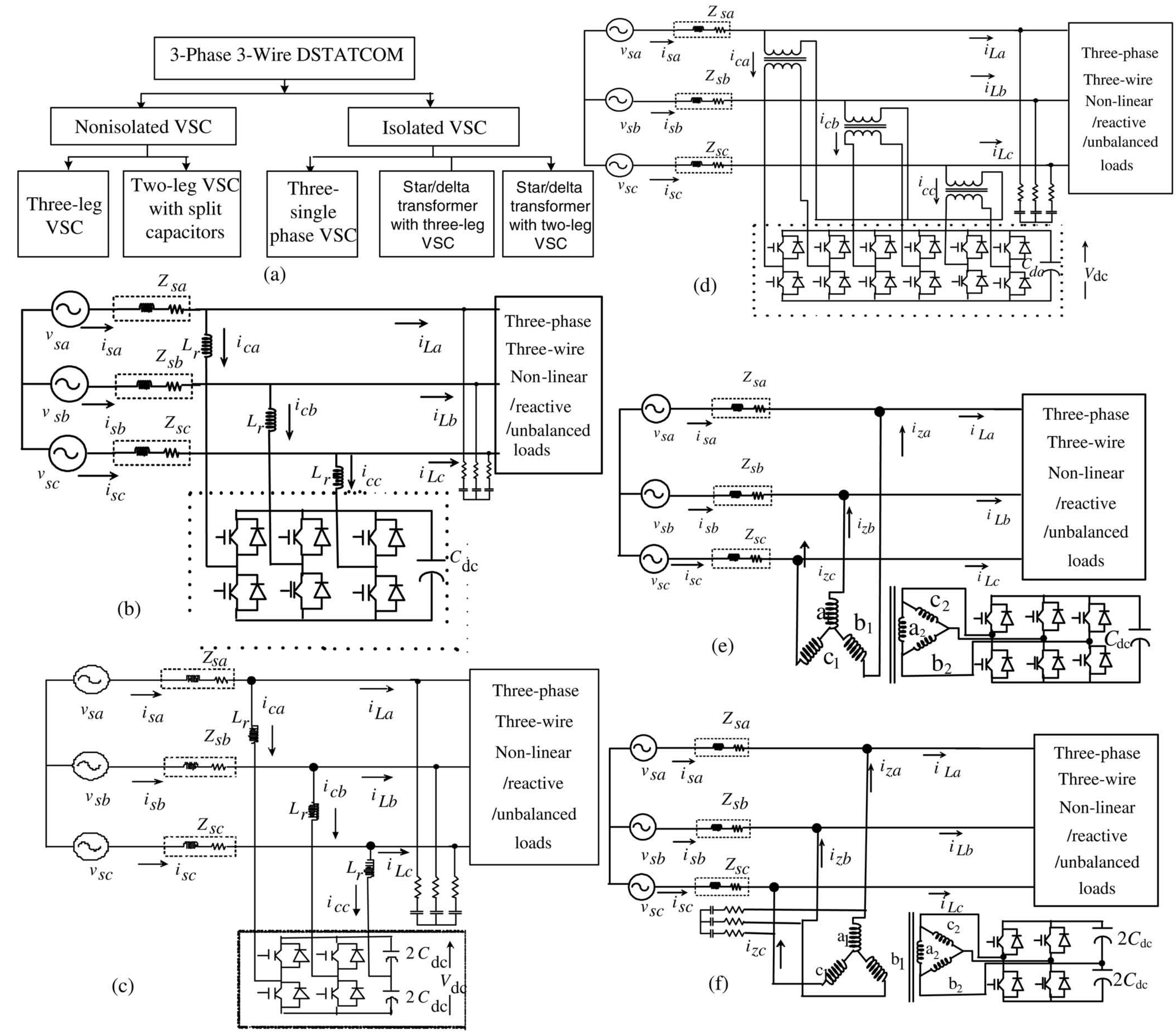


Fig. 1. (a) Classification of three-phase three-wire DSTATCOM, (b) three-leg topology of the three-phase three-wire DSTATCOM, (c) two-leg with split capacitor, (d) three single-phase topology, (e) isolated three-leg VSC, and (f) isolated two-leg VSC.

four-wire DSTATCOM as shown in Fig. 4(c) and (d), respectively. The advantages of zig-zag transformer are also applicable to other transformer configurations.

3) Nonisolated Two-Leg VSC With Transformers [113]–[116]: A two-leg VSC with split capacitors and a zig-zag transformer is used as three-phase four-wire DSTATCOM as shown in Fig. 4(e) [113]. A zig-zag transformer and the other transformers such as star/delta transformer, T-connected transformer, and star/hexagon transformer along with two-leg VSC as three-phase four-wire DSTATCOM are shown in Fig. 4(f) [114], (g) [115], and (h) [116], respectively. The number of power electronics switches is less here compared to three-leg VSC-based topologies.

4) Isolated Three Single-Phase VSCs: Three single-phase VSCs as three-phase four-wire DSTATCOM are also reported in [12] and [117], and this topology is shown in Fig. 5(a). The DSTATCOM consists of three H-bridge VSCs that are supported by a common dc storage capacitor. Three single-phase transformers are connected to the outputs of these converters to provide isolation between them and also to provide inductance between the PCC and the VSCs.

5) Isolated Three-Leg VSC With Transformers [118]–[123]: A topology of three-phase four-wire DSTATCOM based on three-leg VSC connected to the secondary of a zig-zag transformer is shown in Fig. 5(b) [118], [119]. The other transformers such as star/delta transformer, T-connected transformer, and star/hexagon transformer are also used along with isolated three-leg VSC as three-phase four-wire DSTATCOM as shown in Fig. 5(c) [120], (d) [121], and (e) [122], [123], respectively. The transformer provides isolation from the system and also provides the flexibility to use an "off-the-shelf" VSC for some of the desired applications.

6) Isolated Two-Leg VSC With Transformers [124]–[126]: Isolated H-bridge VSC with split capacitors is used along with a

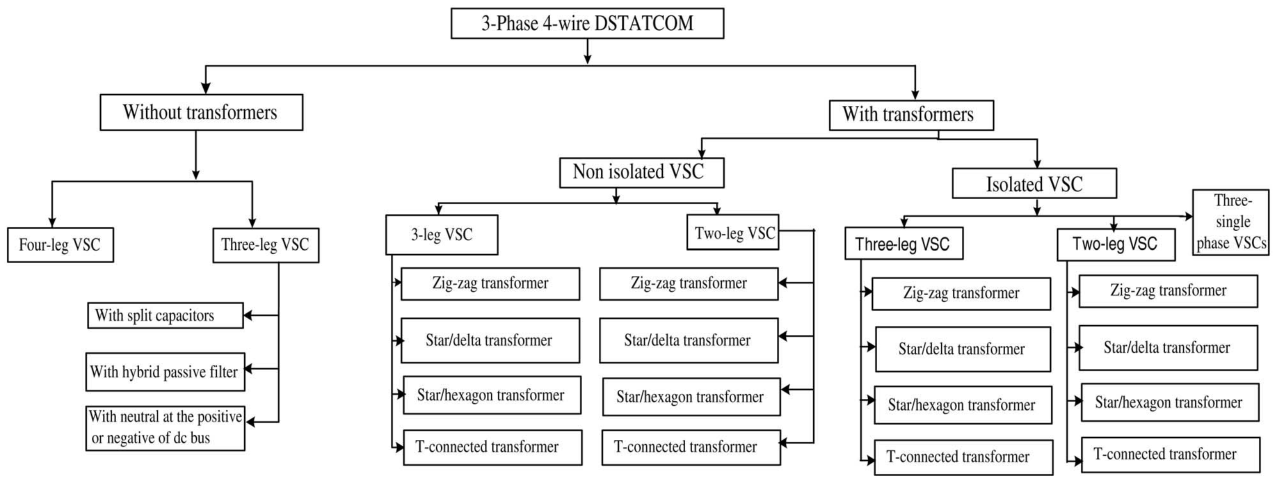


Fig. 2. Classification of three-phase four-wire DSTATCOM.

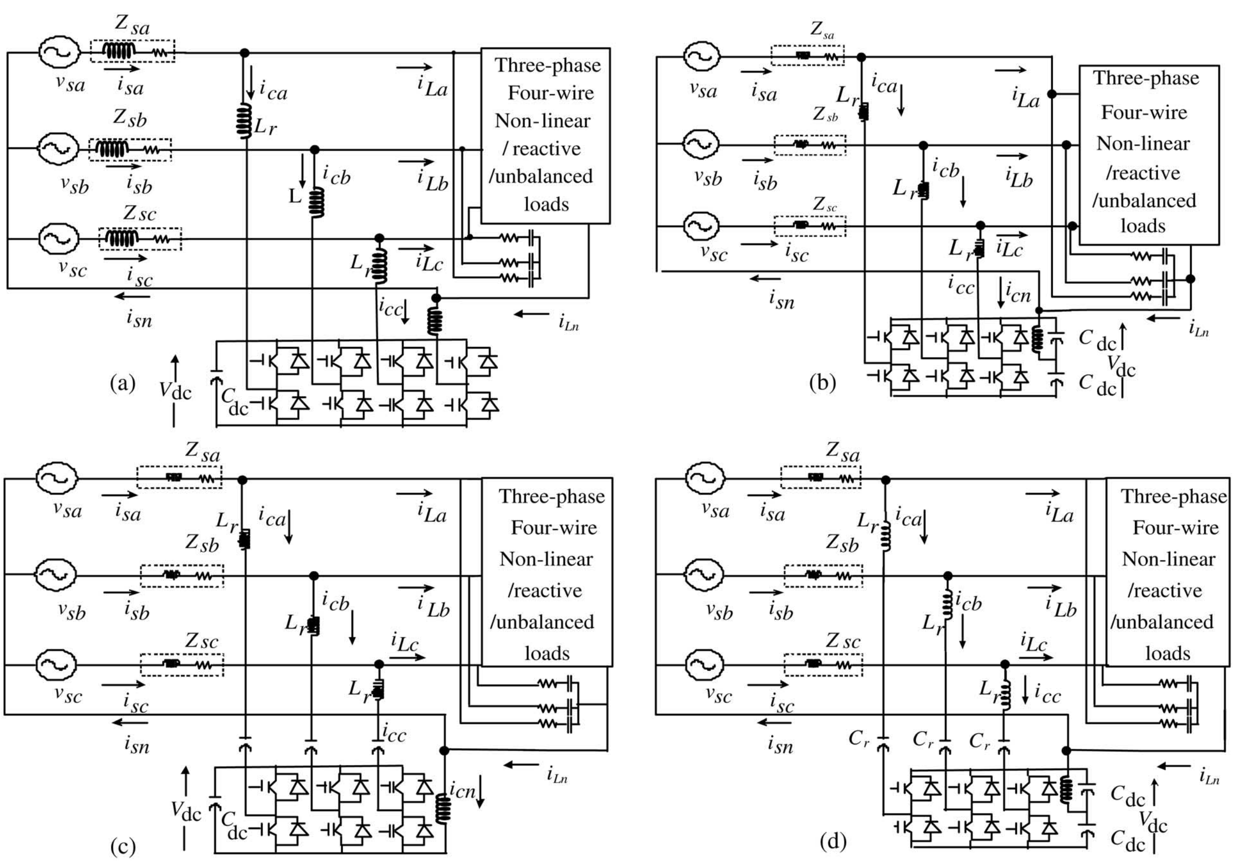


Fig. 3. Topologies of three-phase four-wire DSTATCOM: (a) four-leg VSC-based; (b) three-leg VSC with split capacitors; (c) three-leg VSC with neutral terminal at the dc bus; and (d) three-leg VSC with three dc capacitors.

transformer as three-phase four-wire DSTATCOM. The number of semiconductor devices of VSC is reduced. An H-bridge VSC connected to the secondary of a zig-zag transformer is used as three-phase four-wire DSTATCOM as shown in Fig. 5(f) [124]. The other transformers such as star/delta transformer [125], T-connected transformer, and star/hexagon transformer [126] are also used along with two-leg VSC as three-phase four-wire DSTATCOM as shown in Fig. 5(g), (h), and (i), respectively. The transformer provides isolation from the system and also provides the flexibility to use an "off-the-shelf" VSC in many applications.

IV. Design Considerations and Comparison

The major components in DSTATCOM are the fast switching semiconductor devices such as insulated gate bipolar transistors (IGBTs) and metal oxide semiconductor field effect transistors (MOSFETs). They are controlled as ON and OFF switches, so that they are used for pulse-width modulation (PWM)-based

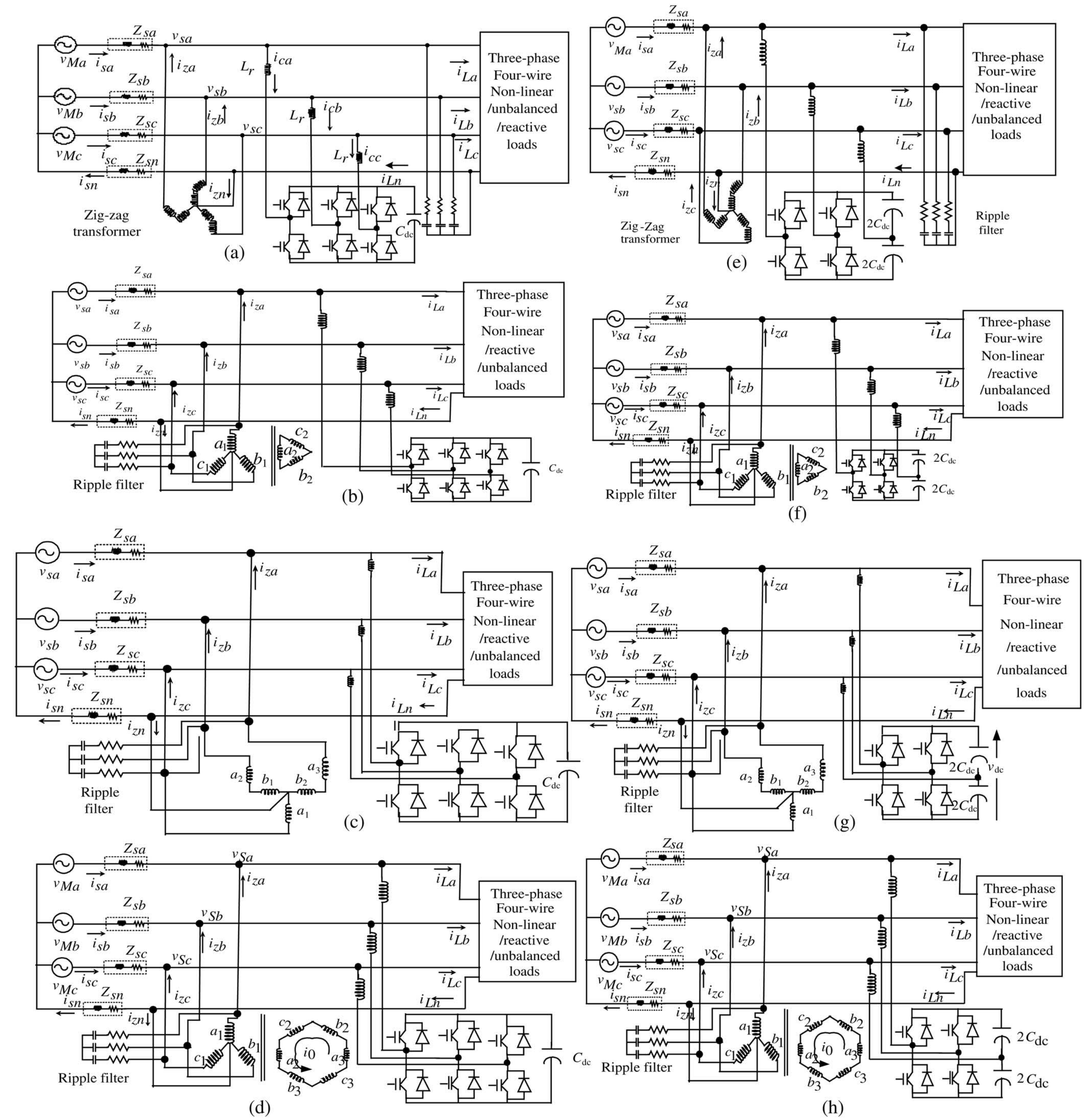


Fig. 4. Topologies for the three-phase four-wire DSTATCOM with nonisolated VSC using transformers: (a) three-leg VSC with zig-zag; (b) three-leg VSC with star-delta; (c) three-leg VSC with T-connected; (d) three-leg VSC with star/hexagon; (e) two-leg VSC with zig-zag; (f) two-leg VSC with star-delta; (g) two-leg VSC with T-connected; and (h) two-leg VSC with star/hexagon.

switching. MOSFETs are used only for small rating, but the IGBTs are used for high power rating. The VSCs, which allow bidirectional power flow, are realized using these devices. Although the heart of the DSTATCOM is the VSC, there are some other components such as interfacing inductors, dc bus capacitor, and coupling transformers.

Depending upon the switching frequency and ripple current, the interfacing inductor is selected and the design of the dc bus capacitor depends on the energy storage capacity needed during transient conditions [56]. The rating of the switches depends on the compensation required for reactive power, harmonics current, and unbalance loading. The voltage rating of the switches depends on the dc bus voltage. The tolerance in the design is also considered, which allows the DSTATCOM power circuit to withstand occurrences of over-current conditions. The switching frequency is selected based on the highest order of harmonics to be eliminated. Moreover, the speed of the processor also affects the switching frequency. In order to avoid violation of current distortion and current control limits, the dc bus voltage is desired to be kept at a minimum voltage [12].

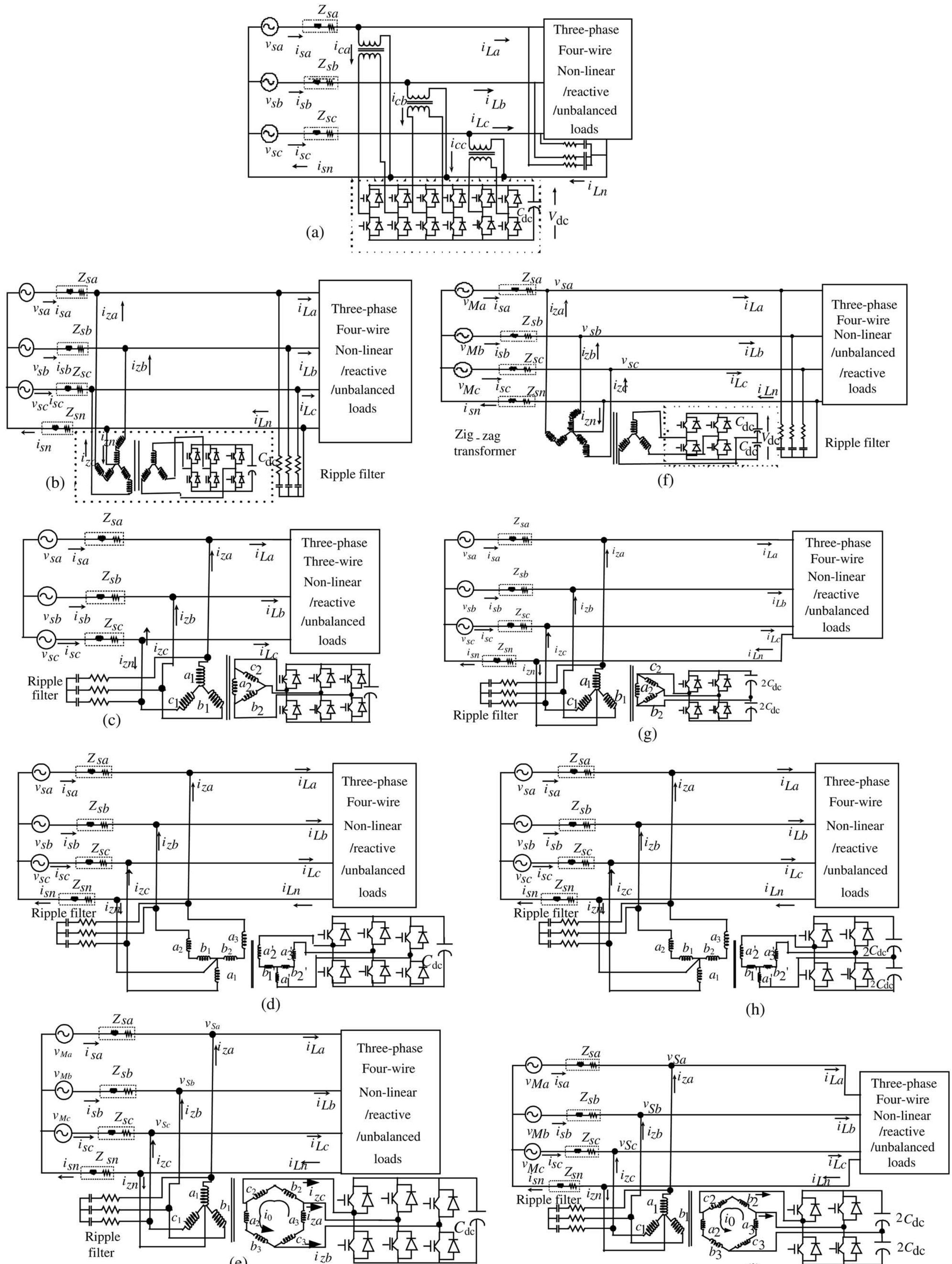


Fig. 5. Topologies for the three-phase four-wire DSTATCOM with isolated VSC using transformers: (a) three-leg VSC with zig-zag; (b) three-leg VSC with star-delta; (c) three-leg VSC with T-connected; (d) three-leg VSC with star/hexagon; (e) two-leg VSC with zig-zag; (f) two-leg VSC with star-delta; (g) two-leg VSC with T-connected; and (h) two-leg VSC with star/hexagon.

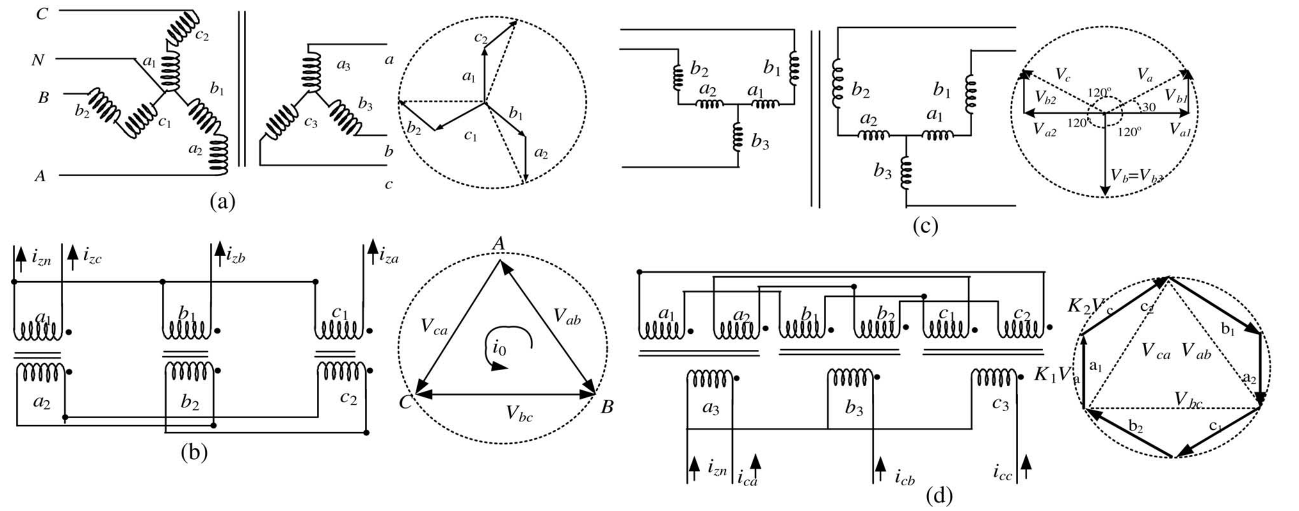


Fig. 6. Isolated transformer and phasor diagram: (a) zig-zag; (b) star/delta transformer; (c) isolated T-connected transformer; and (d) isolated star/hexagon transformer.

A. Design of VSC

The designs of some topologies of DSTATCOM are reported in the literature. However, the component selection for a three-leg VSC used as three-phase three-wire DSTATCOM shown in Fig. 1(b) is given here for a sample calculation. The DSTATCOM is designed for a rating of 12 kVA for the reactive power compensation of the load given in Appendix. The dc bus voltage, dc bus capacitor, and interfacing inductor are selected as follows.

1) dc Capacitor Voltage: The minimum dc bus voltage should be greater than twice of the peak of the phase voltage of the system [111]. The dc bus voltage is calculated as

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

where m is the modulation index and is considered as 1. Thus, $V_{\rm dc}$ is selected as 700 V for a $V_{\rm LL}$ of 415 V.

2) dc Bus Capacitor: The value of dc capacitor ($C_{\rm dc}$) depends on the instantaneous energy available to the DSTATCOM during transients [111]. The principle of energy conservation is applied as

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

where $V_{\rm dc}$ is the reference dc voltage and $V_{\rm dc1}$ is the minimum voltage level of dc bus, "a" is the over loading 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 dc bus, $V_{\rm dc1} = 690$ V, and $V_{\rm dc} = 700$ V, $V = 239.60$ V, $I = 27.82$ A, $t = 350$ μs, $a = 1.2$, the calculated value of $C_{\rm dc}$ is approximately 3000 μF.

3) ac Inductor: The selection of the ac inductance (L_f) depends on the current ripple [111] $i_{{\rm cr},p-p}$, switching frequency f_s, and dc bus voltage ($V_{\rm dc}$), and the L_f is given as

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

where m is the modulation index and a is the over load factor. Considering $i_{{\rm cr},p-p} = 5\%$, $f_s = 10$ kHz, $m = 1$, $V_{\rm dc} = 700$ V, and $a = 1.2$, the L_f value is approximately 2.5 mH.

B. Design of Transformers

The transformers are used in two ways: 1) nonisolated condition for compensating the neutral current only; and 2) use it for providing isolation to the VSC along with neutral current compensation. Transformers are to be designed for the magneto motive force (mmf) balance to achieve the neutral current compensation. The designs of the transformers are given as follows.

1) Zig-Zag Transformer [106]: The connection of the zig-zag transformer and its phasor diagram is shown in Fig. 6(a). If V_a, V_b, and V_c are the voltages across each winding and V_{za} is the resultant voltage, then

$$V_{za} = K_1V_a - K_2V_c \tag{4}$$

where K_1 and K_2 are the fractions of winding in the phases. Considering $V_a = V\angle 0^\circ$ and $V_{za} = \sqrt{3}V\angle 30^\circ$, then

$$\sqrt{3}V\angle 30^\circ = K_1V\angle 0^\circ - K_2V\angle -120^\circ. \tag{5}$$

One gets $K_1 = 1$ and $K_2 = 1$.

The voltage per phase is $V_{za} = 415/\sqrt{3} = 239.60$ V, then

$$V_a = V_b = V_c = 239.60/\sqrt{3} = 138.33 \text{ V}. \tag{6}$$

Three single-phase transformers each of rating 1.4 kVA, 140/140 V are selected.

2) Star/Delta Transformer [109]: The connection of the star/delta transformer and its phasor diagram is shown in Fig. 6(b). The current rating of the transformer windings is based on the circulating current due to the zero-sequence components in the load current. The primary winding voltage is

$$V_a = V_{\rm LL}/(\sqrt{3}) = 415/\sqrt{3} = 239.60 \text{ V}. \tag{7}$$

Hence, a 240-V winding is selected in star/delta transformer. The secondary line voltage is chosen for the same current to flow

TABLE I
COMPONENTS AND PARAMETERS OF DSTATCOM

Sl.No	Topology	Transformer	Interfacing Inductance, L (mH)	Capacitor C (μF)	Dc bus voltage, Vdc (V)	Isolat-ion	kVA rating of Tran.	Semiconductor devices
1	Three-leg VSC [Fig.1(b)]	Not required	2.5	3000	700	No	Nil	6
2	Two-leg VSC with split capacitor [Fig.1(f)]	Not required	7	5000	1400	No	Nil	4
3	Four-leg VSC [Fig.2(b)]	Not required	3.5	2200	700	No	Nil	8
4	Non-isolated zig-zag transformer with three-leg VSC [Fig.3(a)]	Zig-zag transformer	3.5	2200	700	No	5	6
5	Non-isolated star/delta transformer with two-leg VSC [Fig.3(f)]	Star/delta transformer	7	5000	1400	No	8	4
6	Three single phase VSC [Fig.4(a)]	Not required	7	2200	400	Yes		12
7	Isolated T-connected transformer with three-leg VSC [Fig.4(d)]	T-connected transformer	2.3	6600	400	Yes	12	6
8	Isolated star/hexagon transformer with two-leg VSC [Fig.4(j)]	Star/hexagon transformer	3.5	6600	400	Yes	12	4

in the windings. The voltage ratio of the transformer is 1:1. Therefore, three numbers of single-phase transformers each of rating 2.4 kVA, 240/240 V are selected.

3) T-Connected Transformer [111]: Fig. 6(c) shows the connection of two single-phase transformers for interfacing with a three-phase four-wire system. The T-connected winding of the transformer provides a path for the zero-sequence fundamental current and harmonics currents and hence offers a path for the neutral current when connected in shunt at PCC. Under unbalanced loads, the zero-sequence load neutral current divides equally into three currents and takes a path through the T-connected windings of the transformer. The current rating of the windings is decided by the required neutral current compensation. The voltage across each winding is designed as shown in Fig. 6.

The phasor diagram shown in Fig. 6(c) gives the following relations to find the turn's ratio of windings. If V_{a1} and V_{b1} are the voltages across each winding and V_a is the resultant voltage, then

$$V_{a1} = V_a \cos 30^\circ \tag{8}$$
$$V_{b1} = V_b \sin 30^\circ. \tag{9}$$

Considering $|V_a| = |V_b| = V$, the line voltage is $V_{ca} = 415$ V, then

$$V_a = V_b = V_c = 415/\sqrt{3} = 239.60 \text{ V} \tag{10}$$
$$V_{a1} = 207.49 \text{ V}, \quad V_{b1} = 119.80 \text{ V}. \tag{11}$$

Hence, two single-phase transformers of rating 2.4 kVA, 240/120/120 V and 2.1 kVA, 208/208 V are selected.

4) Star/Hexagon Transformer [122]: The hexagon-connected secondary winding of the transformer provides a path for the zero-sequence fundamental current and harmonic currents and hence offers a path for the neutral current when connected in shunt at PCC. Under single-phase load, the zero-sequence load neutral current circulates in the hexagon windings of the star/hexagon transformer. The voltage across each primary winding is the phase voltage. The voltage rating of the star/hexagon transformer windings is designed as shown in Fig. 6.

The star/hexagon transformer and the phasor diagram shown in Fig. 6(d) explain the following relations to find the turns ratio of windings. If V_a, V_b, and V_c are the per-phase voltages across each winding and V_{ca} is the resultant voltage, then

$$V_{ca} = K_1 V_a - K_2 V_c \tag{12}$$

where K_1 and K_2 are the fractions of winding in the phases. Considering $V_a = V\angle 0^\circ$ and $V_{za} = \sqrt{3}V\angle 30^\circ$, then

$$\sqrt{3}V\angle 30^\circ = K_1 V\angle 0^\circ - K_2 V\angle -120^\circ. \tag{13}$$

One gets $K_1 = 1$ and $K_2 = 1$.
The line voltage is $V_{ca} = 200$ V, then

$$V_a = V_b = V_c = 200/\sqrt{3} = 115.50 \text{ V}. \tag{14}$$

Hence, three numbers of single-phase transformers each of rating 2.6 kVA, 240/120/120 V are selected.

C. 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 for the harmonic voltage at a frequency of 5 kHz, the ripple filter capacitor is designed as $C_f = 5\ \mu$F [111]. A series resistance (R_f) of 5Ω is included in series with the capacitor (C_f).

D. Comparison of Topologies

The components and voltage levels for the different topologies are summarized in Table I. The number of required switching devices, required transformer, interfacing inductor, dc bus voltage, dc bus capacitance, and kilovolt ampere rating of the transformer is tabulated for a quick comparison. It is observed that the lower dc bus voltage is possible with isolated VSC-based DSTATCOMs. The number of semiconductor devices is minimum with two-leg VSC-based DSTATCOMs.

V. CONTROL METHODS OF DSTATCOM

There are different control strategies reported such as sliding mode control, voltage template and PI controllers, instantaneous symmetrical component theory, and neural network

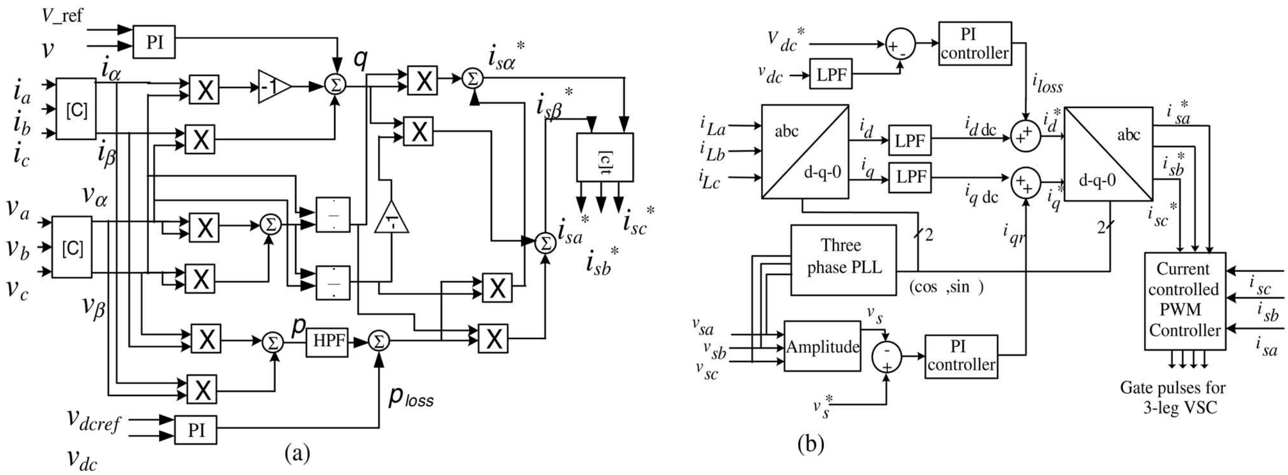


Fig. 7. (a) Block diagram of IRPT-based control of DSTATCOM and (b) block diagram of SRFT-based control of DSTATCOM.

theory. Some important control strategies are given in the following sections.

A. Instantaneous p–q Theory [52]

The control of DSTATCOM is implemented on the basis of instantaneous reactive power theory (or $p-q$ theory) to calculate the desired compensation current. The block diagram for the control using IRPT is shown in Fig. 7(a). In this method, the sensed three-phase PCC voltages and load currents are transformed into $\alpha - \beta - o$ axis using Clark's transformation. In addition, the source must deliver no zero-sequence active power (so that the zero-sequence component of the voltage at the PCC does not contribute to the source power). The reference source currents in the $\alpha - \beta - o$ reference frame are converted to the abc frame using the reverse Clark's transformation.

B. SRF Theory [53]

This control technique is based on the transformation from abc frame to the rotating reference frame $d - q - 0$ using the unit vectors $\cos\theta$ and $\sin\theta$ obtained using a three-phase phase-locked loop (PLL) of supply voltage. A block diagram of the control scheme is shown in Fig. 7(b). The oscillatory components (ac components) are eliminated using low-pass filter (LPF) and the dc component is the fundamental frequency part of the load current.

C. Voltage Template and Proportional-Integral (PI) Controllers [56]

This method is based on the unit vectors derived from the supply voltage. The in-phase and quadrature unit sine waves are generated. There are two PI controllers used over the dc bus voltage and the amplitude of supply voltage, respectively. The in-phase component of the reference source current is obtained by multiplying the dc bus PI controller output with the in-phase unit vectors, and the quadrature component of the reference source current is obtained by multiplying the ac amplitude PI controller output with the quadrature unit vectors. The reference supply currents are derived as the sum of the in-phase and quadrature components of currents.

D. Instantaneous Symmetrical Components Theory [9]

This method is based on the power calculated using the fundamental positive-sequence component the voltage at the PCC. This method is capable of providing perfect harmonic cancellation. Its objective is to compensate all the harmonics currents and the fundamental reactive power demanded by the load in addition compensating the imbalance.

E. Adaline-Based Neural Network [65]

The extraction of balanced positive sequence fundamental frequency component of the load currents is carried out using artificial neural network (ANN) based on least-mean-square (LMS) algorithm known as Adaline (Adaptive Linear Element) technique. It is based on online estimation of weights corresponding to real fundamental frequency component. The Adaline has been trained at fundamental frequency of positive sequence in-phase and quadrature with voltage. The technique is demonstrated to selectively compensate the current harmonics, load unbalance, and reactive power based on priority.

VI. Selection Considerations

The selection of a suitable DSTATCOM topology and control technique is an important task for users and designers. Obviously, there is a segregation between three-phase three-wire and three-phase four-wire DSTATCOMs. The considerations such as isolated and nonisolated topologies of DSTATCOM are critical. The isolation with a transformer (star/delta, zig-zag, star/hexagon, T-connected) provides the flexibility for the use of "off-the-shelf" three-leg VSC or two-leg VSC for realizing a three-phase four-wire DSTATCOM. The two-leg, H-bridge VSC-based transformer isolated three-phase four-wire DSTATCOM is advantageous in terms of cost, size, and weight. But, the control of equal dc bus voltages and the higher voltage rating of switching devices are the factors to be considered in selecting these configurations.

TABLE II
COMPARISON OF TRANSFORMERS FOR NEUTRAL CURRENT COMPENSATION

Transformer	Winding voltage(V)	Winding current(A)	kVA	Number of transformers	Total kVA
Zig-zag	140/140	10	1.4	3 Nos	4.2
Star/delta	240/240	10	2.4	3 Nos	7.2
T-connected	240/120/ 120 208/208	10	2.4 2.08	1 Nos 1Nos	4.48
Star/hexagon	240/140/ 140	10	2.4	3 Nos	7.8

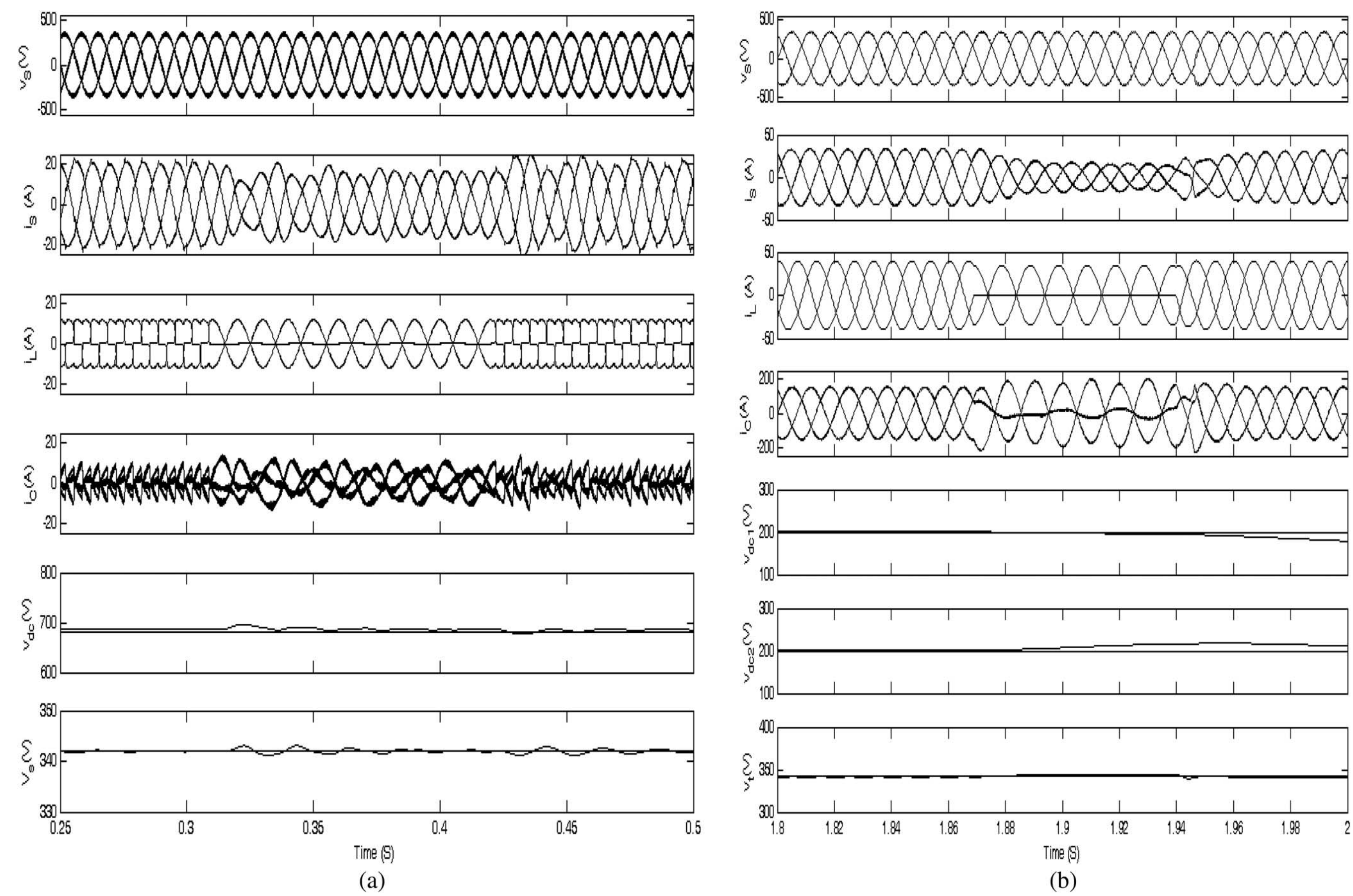


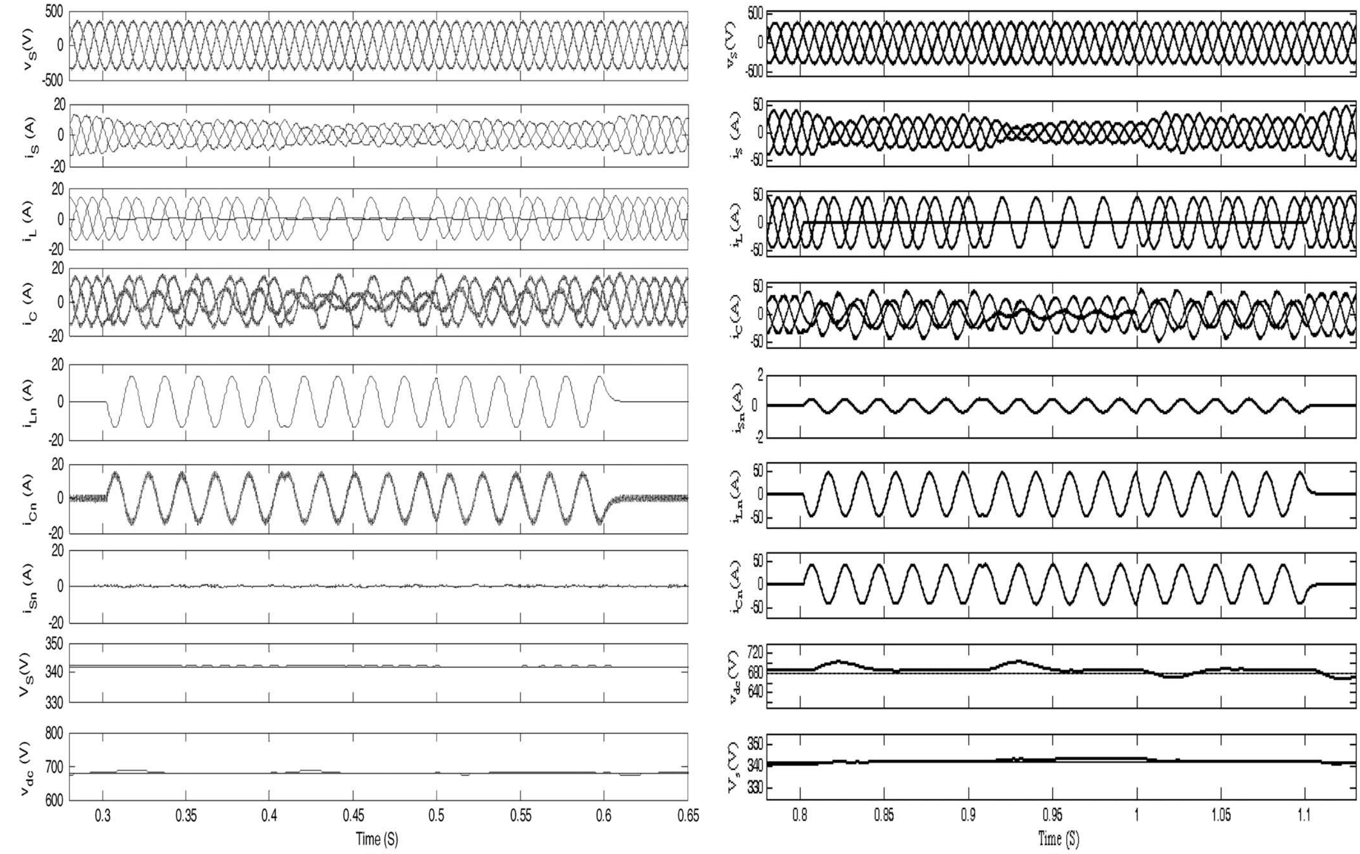
Fig. 8. (a) Three-leg VSC-based three-phase three-wire DSTATCOM for harmonics compensation and voltage regulation under nonlinear loads; and (b) isolated two-leg VSC and split capacitors-based three-phase three-wire DSTATCOM for load balancing and voltage regulation under linear loads.

The kilovolt ampere rating of the transformer is also a major consideration. A comparison of kilovolt ampere rating of the transformers for the given system is given in Table II. It is observed that the zig-zag transformer has the lowest rating followed by the T-connected transformer. The star/delta and star/hexagon transformers have higher rating. But a star/delta transformer is commonly available in the market. Similarly, some other considerations such as comparative features of other option and types of protection are to be followed.

VII. Future Developments and Potential Applications

The DSTATCOM is observed to be very effective for power quality improvement such as power factor correction, load balancing, harmonics elimination, and neutral current compensation in the distribution systems. The scope of custom power devices in the distribution system is enormous. Although the cost of the DSTATCOM is little higher at present, however in future, it will be an attractive remedy for such problems faced by the present day distribution system.

Moreover, DSTATCOM is proposed for power quality improvement in the distributed generation system and one such application is for diesel engine-based electricity generation unit (DG set) [55]. The DSTATCOM can be used with self-supporting dc bus or BESS to improve power quality of DG set. The DSTATCOM with three-phase DG set can feed unbalanced and nonlinear loads without derating the DG set and with the same cost involved.



(a) (b)

Fig. 9. (a) Performance of four-leg VSC-based three-phase four-wire DSTATCOM for neutral current compensation, load balancing, and voltage regulation under linear loads; and (b) performance of nonisolated three-leg VSC and zig-zag transformer as DSTATCOM for neutral current compensation, load balancing, and voltage regulation under linear loads.

The distributed generators using renewable energy sources such as micro-hydro turbines [56], wind turbines, and so on, have been developed and installed on utility power distribution systems. The active power influenced by weather and/or wind velocity causes voltage fluctuations in the distribution line, because it changes independently the power demand from loads. This makes difficulty in voltage regulation throughout multiple distribution lines and hence DSTATCOM is an effective solution for these problems.

VIII. Performance of DSTATCOMS

Some of the three-phase three-wire and three-phase four-wire DSTATCOMs selected from each category are designed and modeled using MATLAB software with its Simulink and Power System Blockset (PSB) toolboxes. Topologies shown in Fig. 1(b) and (f) are selected for three-phase three-wire DSTATCOM and topologies shown in Figs. 3(a), 4(a), 4(f), 5(a), 5(d), and 5(i) are selected for three-phase four-wire DSTATCOM. Then performance study is carried out using simulations for the given system shown in Appendix.

A. Three-Phase Three-Wire DSTATCOM

The dynamic performance of three-leg VSC-based DSTATCOM [topology shown in Fig. 1(b)] for voltage regulation along with harmonics compensation and load balancing is shown in Fig. 8(a). The loads are considered as nonlinear loads. It is demonstrated for voltage regulation along with harmonics reduction and load balancing. The PCC voltages (v_S), supply currents (i_S), harmonic load currents (i_L), compensator currents (i_C), dc bus voltage ($v_{\rm dc}$), and amplitude of voltage (V_S) at PCC are depicted in Fig. 8(a). The supply currents are observed as sinusoidal and balanced, though the load currents are nonlinear and unbalanced. The dc bus of the VSC is self-supported and its voltage is regulated to the reference value under varying loads.

The dynamic performance of a three-phase three-wire DSTATCOM based on isolated H-bridge VSC and a star/delta transformer [topology shown in Fig. 1(f)] is shown in Fig. 8(b). The considered loads are linear loads. The split capacitors are maintained at equal dc voltages of 200 V and the total dc bus voltage is 400 V. The amplitude of voltage (V_S) is regulated to a reference value under varying loads demonstrating the voltage regulation operation of the DSTATCOM.

B. Three-Phase Four-Wire DSTATCOM

The performance of six topologies of three-phase four-wire DSTATCOMs is demonstrated from each category for power factor correction or voltage regulation by reactive power compensation along with harmonics elimination, load balancing, and

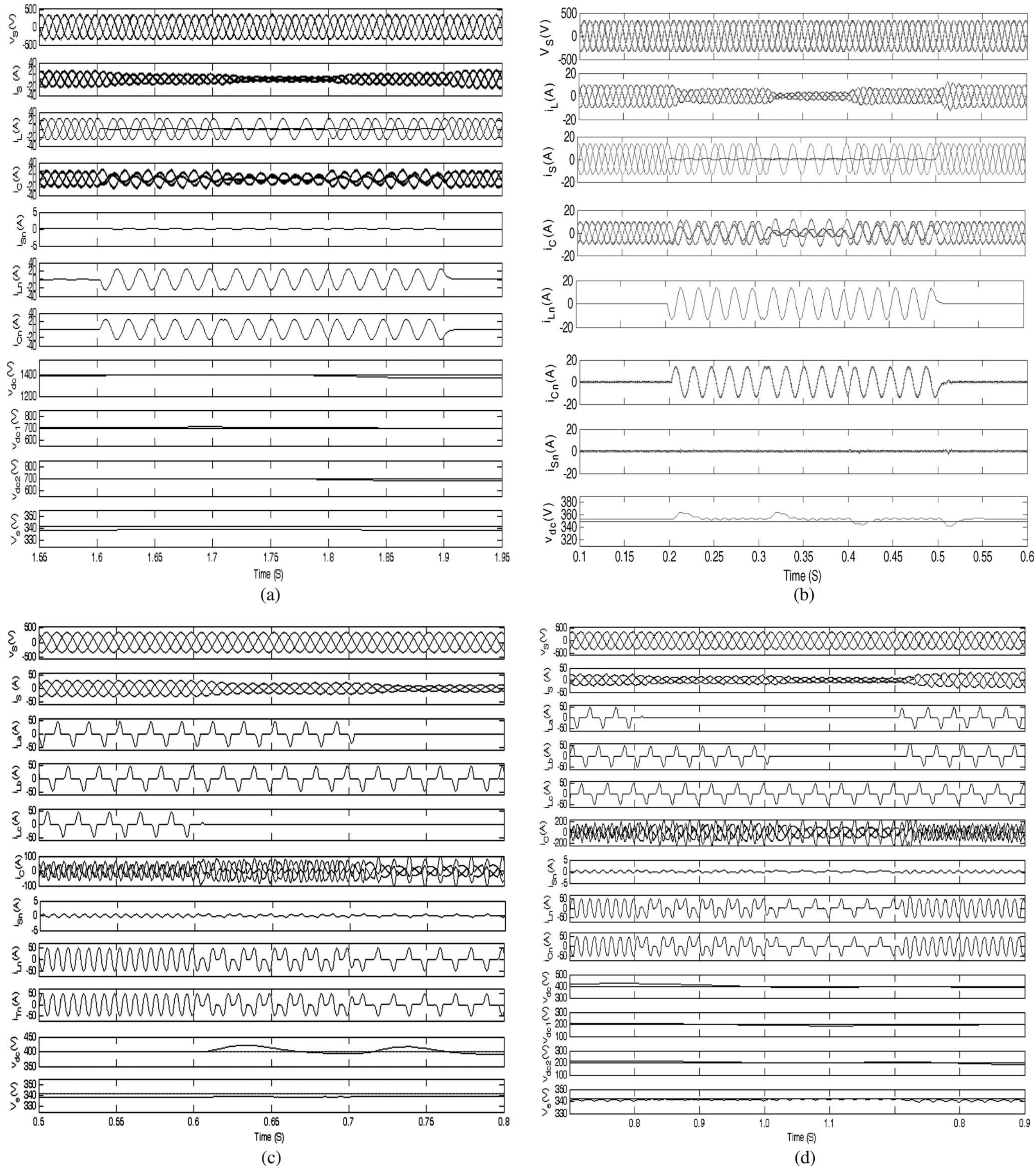


Fig. 10. (a) Performance of nonisolated two-leg VSC and star/delta transformer as DSTATCOM for neutral current compensation, load balancing, and power factor correction; (b) performance of three single-phase VSC-based DSTATCOM for neutral current compensation, load balancing, and power factor correction; (c) performance of isolated three-leg VSC and T-connected transformer as DSTATCOM for neutral current compensation, load balancing, and power factor correction under nonlinear loads; and (d) performance of isolated two-leg VSC and star/Hexagon transformer as DSTATCOM for neutral current compensation, load balancing, and voltage regulation under nonlinear loads.

neutral current compensation. The PCC voltages (v_S), load currents (i_L), supply currents (i_S), compensator currents (i_C), load neutral current (i_{Ln}), compensator neutral current (i_{Cn}), supply neutral current (i_{Sn}), amplitude of voltage (V_t) at PCC and dc bus voltage (v_{dc}) are depicted in each case. The performance is analyzed in the following sections.

1) Nonisolated Four-Leg VSC: The dynamic performance of a four-leg VSC-based DSTATCOM [topology shown in

Fig. 3(a)] for voltage regulation along with load balancing is shown in Fig. 9(a) under linear loads. It is observed that DSTATCOM has regulated PCC voltage by injecting reactive power. The supply currents are balanced when the load currents are unbalanced. Moreover, the dc bus voltage is regulated under varying loads.

2) Nonisolated Three-Leg VSC With Zig-Zag Transformer: The dynamic performance of three-leg VSC with zig-zag transformer [topology shown in Fig. 4(a)]-based DSTATCOM for PCC voltage regulation along with load balancing is shown in Fig. 9(b) at linear loads. Supply currents are observed to be balanced when the load currents are unbalanced. Moreover, the neutral current is compensated by the zig-zag transformer.

3) Nonisolated Two-Leg VSC and Star/Delta Transformer: The dynamic performance of a two-leg VSC and star/delta transformer-based DSTATCOM [topology shown in Fig. 4(f)] for power factor correction along with load balancing is shown in Fig. 10(a) under linear loads. The supply currents are balanced even when load currents are unbalanced. Moreover, the neutral current is compensated by a star/delta transformer.

4) Three Single-Phase VSC: The dynamic performance of a three single-phase VSC-based three-phase transformer [topology shown in Fig. 5(a)] for voltage regulation operation along with load balancing and neutral current compensation is shown in Fig. 10(b) under linear loads. It is observed that supply currents are maintained balanced and sinusoidal and the neutral current is compensated even under unbalanced load currents. Moreover, the dc bus is self-supported and its voltage is regulated to the reference value under varying loads.

5) Isolated Three-Leg VSC With T-Connected Transformer: The dynamic performance of three-leg VSC with T-connected transformer [topology shown in Fig. 5(d)]-based DSTATCOM for power factor correction along with load balancing and harmonics compensation is shown in Fig. 10(c). These loads are considered as nonlinear loads in order to demonstrate harmonics elimination. The supply currents are balanced and sinusoidal even when the load currents are unbalanced and having harmonics. Moreover, the neutral current is compensated by the T-connected transformer.

6) Isolated Two-Leg VSC With Star/Hexagon Transformer: The dynamic performance of an isolated two-leg VSC with star/hexagon transformer [topology shown in Fig. 5(i)]-based DSTATCOM for voltage regulation along with harmonics compensation and load balancing is shown in Fig. 10(d). These loads are considered as nonlinear loads in order to demonstrate harmonics elimination. The neutral current is compensated by a star/hexagon transformer. Moreover, the supply currents are observed to be balanced and sinusoidal even when load currents are nonlinear and unbalanced.

C. Comparison of Performances of DSTATCOMs

It has been observed that the dc bus voltage of VSC is regulated under all conditions of varying loads, verifying the self-supporting operation of all DSTATCOMs. The topology shown in Fig. 1(f) is advantageous as three-phase three-wire DSTATCOM, because it has least numbers of semiconductor devices and hence less cost, but it has a bulky transformer. The three-leg VSC-based DSTATCOM shown in Fig. 1(b) is preferred when a transformer is not preferred.

Similarly, when the transformer is not preferred for a three-phase four-wire DSTATCOM, a four-leg VSC-based topology shown in Fig. 3(a) is preferred. Otherwise, the isolated zig-zag transformer and H-bridge VSC-based topology shown in Fig. 5(f) is advantageous as a three-phase three-wire DSTATCOM, because it has least number of semiconductor devices and the zig-zag transformer has lowest kilovolt ampere rating. Moreover, nonisolated zig-zag transformer and three-leg VSC-based topology shown in Fig 4(a) is found suitable, when isolation is not required for the VSC. The similar topologies with T-connected transformers may be suitable to applications where space occupied by transformers is a constraint, as they require only two single-phase transformers. It is demonstrated using simulations that the performance is unaffected with the selection of transformers, but only the kilovolt ampere rating and number of transformers become the selection criteria.

IX. Conclusion

A comprehensive state of the art of DSTATCOM for power quality improvement in the three-phase power distribution system has been presented to explore the topologies and control techniques. The detailed classification, state of the art, design considerations, and comparison have been given for easy selection of a DSTATCOM for specific applications. The performances of topologies of DSTATCOMs selected from each category have been demonstrated to validate the designed DSTATCOM system. A comparative evaluation has been made with the aim of exploring and exposing the design, model, and simulation. The compensation of reactive power for power factor correction or voltage regulation, harmonics elimination, load balancing, and neutral current compensation has been demonstrated for three-phase three-wire and three-phase four-wire DSTATCOM. It is hoped that these DSTATCOMs along with performance demonstration will be useful to the designers, manufacturers, and researchers dealing with power quality issues in the distribution system.

Appendix

Line impedance: $R_s = 0.01\ \Omega$, $L_s = 2$ mH.

Loads: 1) Linear: 20 kVA, 0.80 pf lag.

2) Nonlinear: Three single-phase bridge rectifier with $R = 25\ \Omega$ and $C = 470\ \mu$F.

Ripple filter: $R_f = 5\ \Omega$, $C_f = 5\ \mu$F.

Three-leg VSC-Based Three-Phase Three-wire DSTATCOM:

Interfacing inductance $= 2.5$ mH.

dc bus capacitance of DSTATCOM: 3000 μF.

dc bus voltage of DSTATCOM: 700 V.

dc voltage PI controller: $K_{pd} = 0.1$, $K_{id} = 0.8$.

PCC voltage PI controller: $K_{pq} = 0.2$, $K_{iq} = 0.5$.

ac line voltage: 415 V, 50 Hz.

PWM switching frequency: 10 kHz.

Zig-zag transformer: Three single-phase transformers of each of rating 1.4 kVA, 140 V/140 V/140 V.

Star-delta transformer: Three single-phase transformers of each of rating 2.4 kVA, 240 V/120 V/120 V.

T-connected transformer: Two single-phase transformers of rating 2.4 kVA, 208 V/208 V and 2.1 kVA, 240 V/120 V/120 V.

Star-hexagon transformer: Three single-phase transformers of each of rating 2.6 kVA, 240 V/120 V/120 V.

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