Exploration of the HBSM MMC Five-Level Inverter for D-STATCOM Application

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ABSTRACT

This paper presents the concert exploration of a Modular Multilevel Converter (MMC) and its application for D-STATCOM. The Half Bridge (HB) sub-module is adopted in the MMC due to its simplicity and low conduction losses. An advanced modulation technique of the Phase Disposition (PD) scheme is applied for the control of the HB MMC switches. The converters are facing DC voltage balance problems under non-linear load conditions. The Proportional and Integral (PI) controller is adopted for the balance of DC voltage. Performance parameters such as apparent power, active power, reactive power, power factor, DC voltage balance, and Total Harmonics Distortion (THD) are presented and compared with the ones of the traditional two-level converter. The proposed scheme is simulated in MATLAB/Simulink.

Keywords-Modular Multilevel Converter (MMC); Half Bridge (HB) sub module; Phase Disposition (PD); PI controller; DC voltage balance

I. INTRODUCTION

A Distribution Static Synchronous Compensator (D-STATCOM), is a compensating device that is typically utilized in distribution networks in order to maintain balance in the flow of reactive power [1-2]. The circuit layout has a significant impact on the D-STATCOM compensation effect, particularly accuracy. The control technique of D-STATCOM has a significant impact not only on the compensation effect but also on the speed with which it is achieved. The conventional reactive power compensation devices all have straightforward constructions, which make them incredibly user-friendly in terms of installation, operation, and upkeep. On the other hand, they can only compensate for preset reactive power and their adjustments cannot be made continuously. In addition, the system suffers from the issue of increasing harmonics. Because of this, it may be unable to satisfy the requirements for the reactive power compensation. The majority of contemporary reactive power compensation systems can be divided into two categories. The first one is referred to as a Static Var Compensator (SVC). It is able to monitor the changes in reactive power and compensate for that power in stages, all while suffering minimal losses and being easy to regulate. It can monitor reactive power variations and compensate reactive power in phases with minimal losses and straightforward regulation. Constant reactive power compensation remains challenging, and when reactive power fluctuates rapidly, the system's reaction time suffers. The second one is known as the static synchronous compensator [3] (STATCOM). In certain groups, it is also referred to as the Static Var Generator (SVG) [1]. The term D-STATCOM refers to a STATCOM that is utilized on the load or distribution side. It consists of a controllable complete bridge circuit that can be connected to the system either directly in parallel or indirectly through reactors. D-STATCOM is able to accomplish the goal of dynamic reactive power compensation due to the way it controls the current on the AC side. D-STATCOM's abilities to continuously monitor reactive power changes; quickly responding to changing conditions, and compensating for harmonics are just some of its many benefits. The D-STATCOM also has a fast response time. For power quality applications, there is a growing interest in the use of multilevel inverters in moderate voltage (less than 36 kV) power converters. If a converter has at least three different voltage levels from its phase to its neutral terminal, then it can be categorized as a multilevel inverter. The lack of need for a coupling transformer in applications involving medium voltage and the relatively low harmonic current content are two of the most significant benefits that multilevel inverters offer.

Realization of re-locatable and cost-effective D-STATCOM devices is made possible in this manner. Hence, the MMC is adopted for D-STATCOM application in this paper.

II. MMC D-STATCOM

The DSTATCOM connection is shunt [5] with regard to the PCC connection. In order to provide reactive power compensation, power factor correction, and harmonic filtering, it provides filter current (i_f) at the Point of Common Coupling (PCC) [6]. The block diagram of a compensated system using D-STATCOM is depicted in Figure1. The filter current (i_f) flowing through interfacing inductor (L_f) is regulated by using three-phase HB MMC. The operation of HB MMC is supported by a DC storage capacitor (C_{dc}) which maintains a steady voltage across the DC-link [17]. The feeder resistance and inductance are denoted as (R_S) and (L_S) respectively.

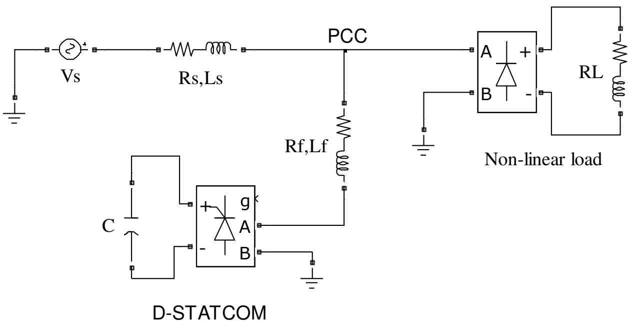

Fig. 1. DSTATCOM configuration.

Figure 2 depicts a structure that is constructed on a three-phase half-bridge sub-module [8]. This construction may be found in the MMC. The corresponding switching states are listed in Table I. Research has been carried out recently to investigate whether or not MMCs and D-STATCOMs based on MMCs are effective in resolving power quality issues such as harmonics, imbalanced DC voltages, and reactive power correction.

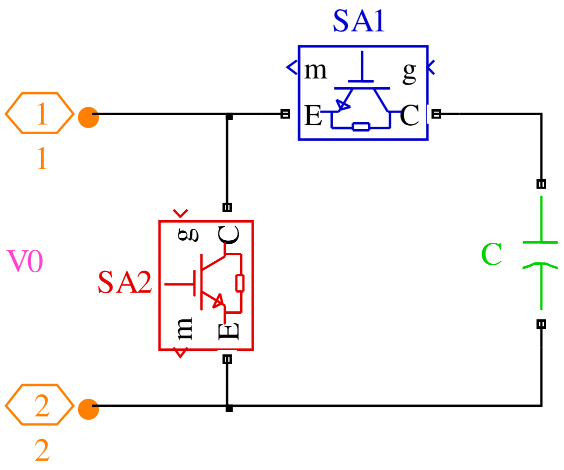

Fig. 2. Half bridge sub-module configuration.

TABLE I. SWITCHING STATES FOR HB SM

Mode	S_{A1}	S_{A2}	Output Voltage
1	1	0	V_0
2	0	1	0

III. CONTROL METHODOLOGY

The actual voltage is kept relatively consistent with the nominal number by the voltage controller. It generates current reference commands and performs Proportional (P) or Proportional Integral (PI) control action in response to errors in voltage signals. The current controller is provided with these reference instructions in order to carry out further controller exploit [9]. The voltage regulator is established with the help of standard control methods in accordance with the system's requirements. By drawing active power from the system, the purpose of the D-STATCOM stratagem is to achieve the goal of delivering the necessary reactive power to the connected loads [10]. The DC link capacitor will show signs of having energy stored in it as a result of the active power being depleted. The coupling association between the DC link and the AC side power determines how the DC link voltage is controlled. Equation (1) provides a mathematical representation of the energy balance:

$$P_{DC} = -P_{AC} \tag{1}$$

The capacitor will retain the energy taken from the terminals as direct current (DC) energy. It has something to do with the side power of AC in the d-q region.

$$P_{DC} = \frac{1}{2} C_{dc} \frac{d}{dt} V_{dc}^2 \tag{2}$$

$$\frac{1}{2} C_{dc} \frac{d}{dt} V_{dc}^2 = -\left(v_d i_d + v_q i_q\right) \tag{3}$$

$$C_{dc} V_{dc} \frac{d}{dt} V_{dc} = -\left(v_d i_d + v_q i_q\right) \tag{4}$$

$$\frac{d}{dt} V_{dc} = \frac{-(v_d i_d + v_q i_q)}{C_{dc} V_{dc}} \tag{5}$$

It is possible to interpret the erroneous input to the PI controller as.

$$\Delta V_{dc} = \left(V_{dcref} - V_{dc}\right) \tag{6}$$

The method of trial and error is used in the process of tuning the PI controller for the DC error. The control structure is illustrated in Figure 4 [11]. The control structure consists of the DC voltage link controller and the PD PWM controller for controlling of the IGBTs of MMC-DSTATCOM. The Phase Disposition (PD) PWM is illustrated in Figure 3.

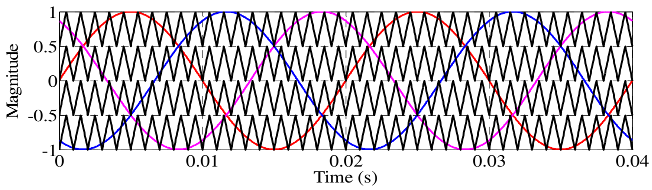

Fig. 3. PD PWM.

IV. RESULT ANALYSIS

The proposed MMC-DSTATCOM configuration as illustrated in Figure 4 [12] was simulated in MATLAB/Simulink. The proposed system was first simulated in uncompensated mode. In this situation, no D-STATCOM is connected. The result is illustrated in Figure 5. The resulting non-linear currents are shown in Figure 5(b). Apparent power [13], active power, reactive power, power factor, and THD are recorded as 6388V A, 5532 W, 3194 VAR, 0.866, and 24.43%, respectively and the outputs are illustrated in Figure 5 [14].

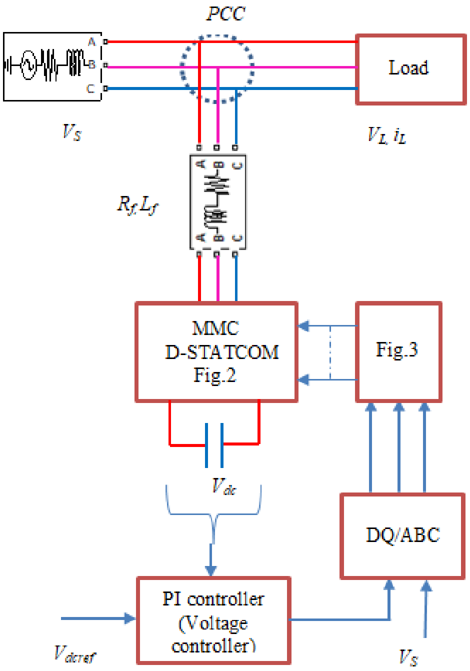

Fig. 4. Control structure of D-STATCOM.

In the second scenario, a D-STATCOM that is based on a two-level voltage source is connected. The outcome of this scenario is depicted in Figure 6 [15]. The resulting non-linear current is shown in Figure 6. Apparent power, active power, reactive power, power factor, and THD are recorded as 6376 VA, 6232 W, 1345 VAR, 0.9775, and 11.76% and their outputs are illustrated in Figure 6 [16]. The active power is improved and the reactive power is reduced. The THD is reduced from 24.43% to 11.76% but this does not satisfy the standards of IEEE. Hence, the five-level HB MMC based D-STATCOM is proposed and simulated to overcome this disadvantage using Hysteresis Current Controller (HCC), as it is simple and easy to implement.

In the third case, the five-level HB MMC based D-STATCOM is connected and its results are illustrated in Figure 7. The resulting non-linear currents are represented in Figure 7. Apparent power, active power, reactive power, power factor, and THD are recorded as 6333 VA, 6233 W, 1117 VAR, 0.9843, and 8.94% and their outputs are illustrated in Figure 7. The active power is improved and the reactive power is reduced. The THD is reduced from 24.43% to 8.94%, but does not satisfy the standards of IEEE. Hence, the five-level HB MMC based D-STATCOM is proposed and simulated to overcome the above disadvantage using the advanced PD PWM modulation scheme.

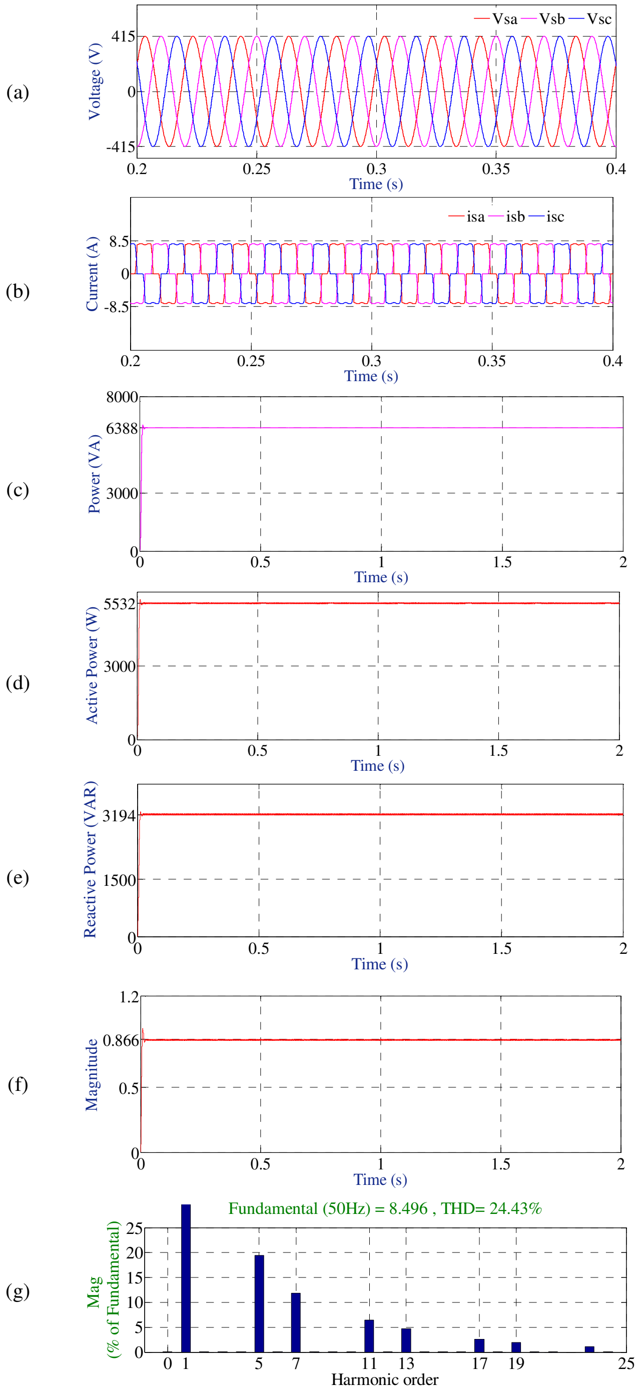

Fig. 5. Response waveforms without D-STATCOM connected. (a) Source Voltage, (b) source current, (c) apparent power, (d) active power, (e) reactive power, (f) power factor, (g) harmonic spectrum of the source current.

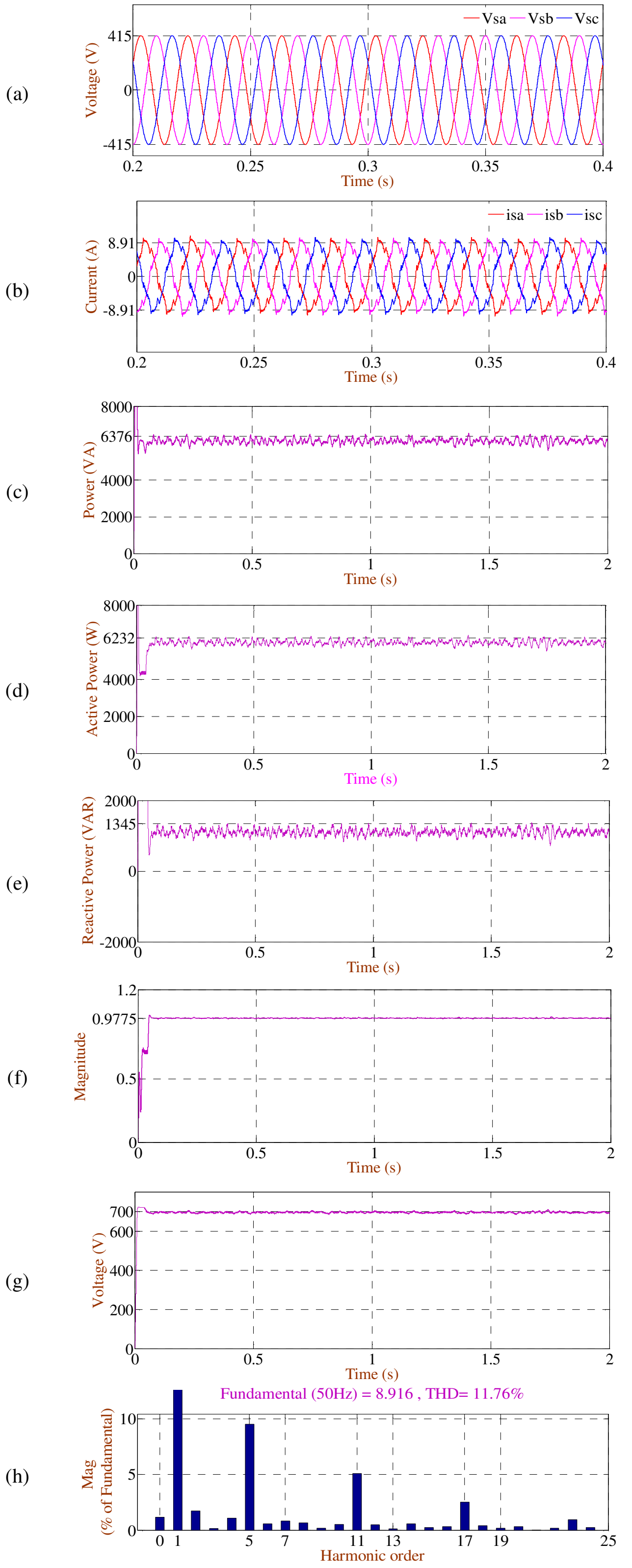

Fig. 6. Response waveforms of two-level VSI-D-STATCOM. (a) Source Voltage, (b) source current, (c) apparent power, (d) active power, (e) reactive power, (f) power factor, (g) DC Voltage, (h) Harmonic spectrum of the source current.

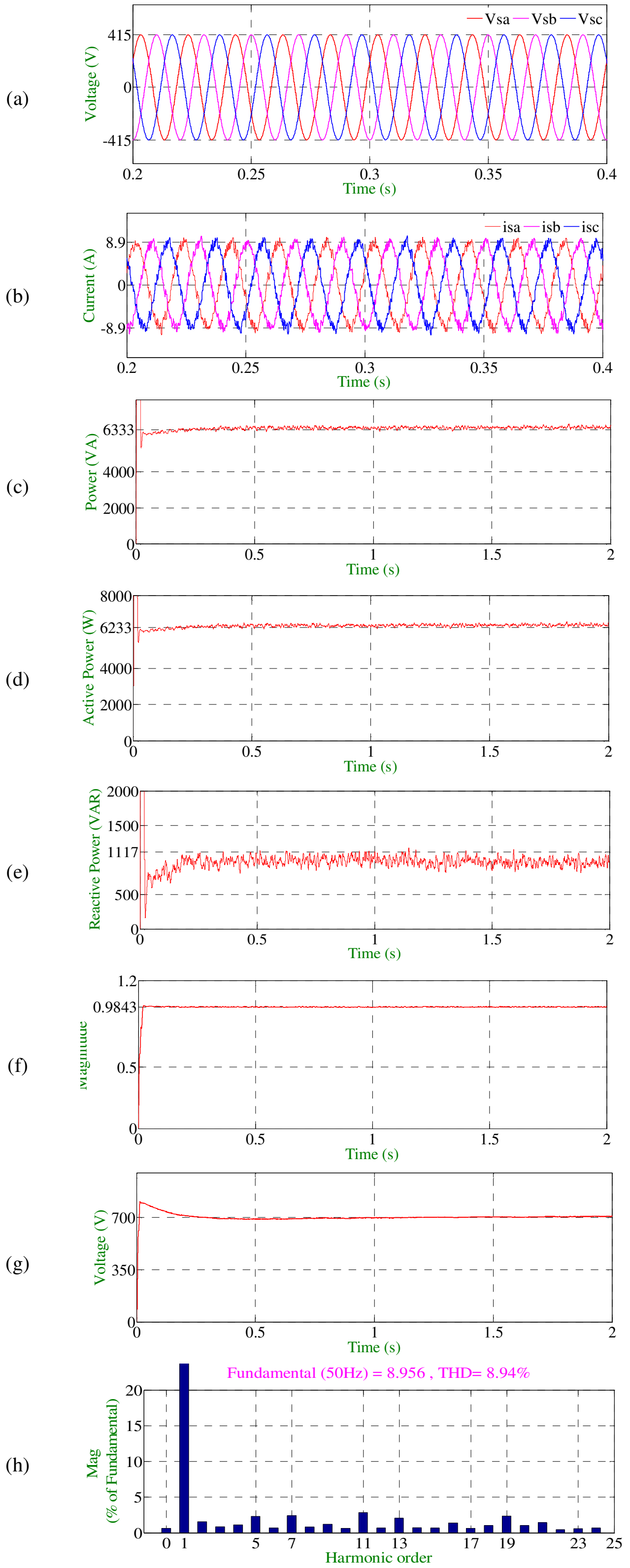

Fig. 7. Response waveforms of five-level HBMMC-D-STATCOM using HCC. (a) Source Voltage, (b) source current, (c) apparent power, (d) active power, (e) reactive power, (f) power factor, (g) DC Voltage, (h) Harmonic spectrum of the source current.

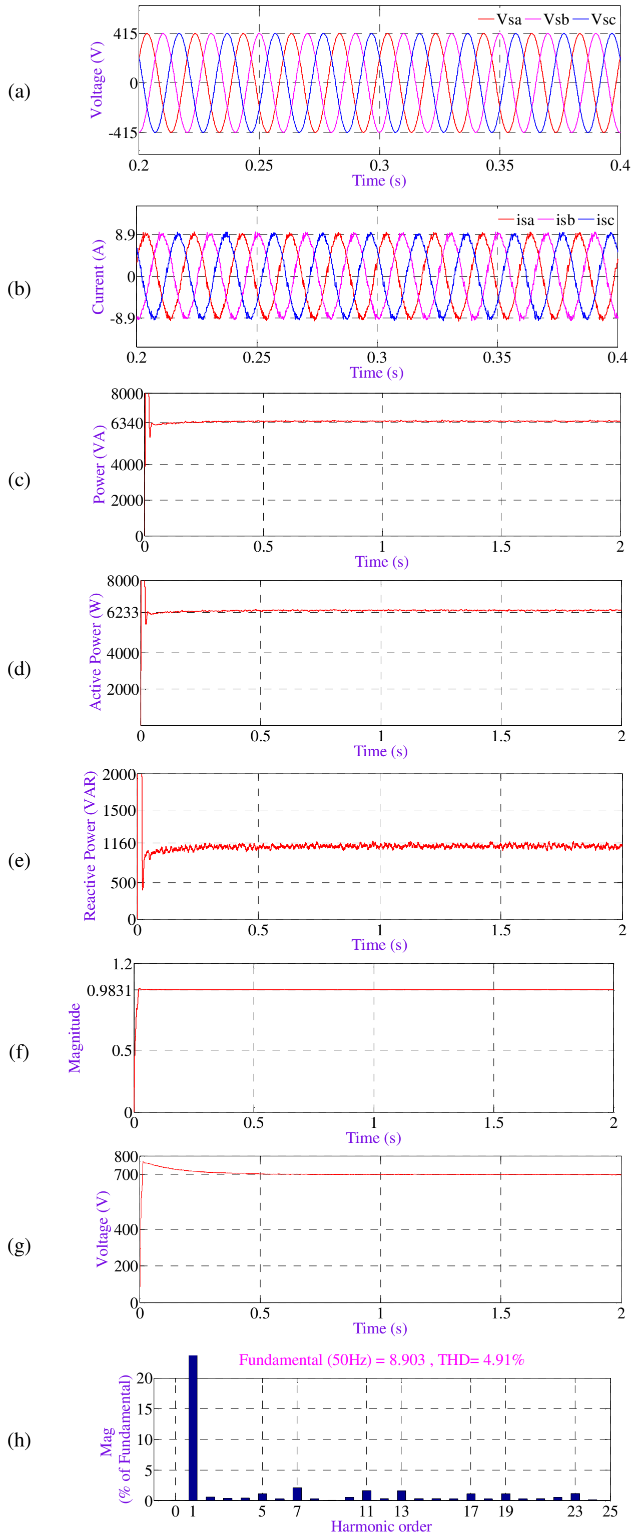

Fig. 8. Response waveforms of five-level HBMMC-DSTATCOM using PD PWM. (a) Source Voltage, (b) source current, (c) apparent power, (d) active power, (e) reactive power, (f) power factor, (g) DC Voltage, (h) Harmonic spectrum of the source current.

In the fourth case, the five-level HB MMC based D-STATCOM using PD PWM is simulated and the results are illustrated in Figure 8 [17]. Apparent power, active power, reactive power, power factor, and THD are recorded as 6340 VA, 6233 W, 1160 VAR, 0.9831, and 4.91% and their outputs are illustrated in Figure 8 along with the source current [18]. The active power is improved and the reactive power is reduced. The THD is reduced from 24.43% to 4.91%, satisfying the standards of IEEE. The complete comparison of all cases is exhibited in Table II.

TABLE II. PERFORMANCE COMPARISON

Parameter		**Before compensation**	**2-level VSI**	**HB MMC 5-level inverter HCC**	**HB MMC 5-level inverter CBPWM**
S (VA)		6388	6376	6333	6340
P (W)		5532	6232	6233	6233
Q (VAR)		3194	1345	1117	1160
PF		0.866	0.9775	0.9843	0.9831
i_{sa} (A)		8.496	8.91	8.956	8.903
Source current harmonics (% values)	I_{h5}	19.45	9.50	2.33	1.09
	I_{h7}	11.81	0.85	2.43	2.10
	I_{h11}	6.49	5.09	2.83	1.63
	I_{h13}	4.71	0.13	2.01	1.52
	I_{h17}	2.59	2.52	0.61	1.10
	THD	24.43	11.76	8.94	4.91

V. DISCUSSION

MMCs are commonly used nowadays in power quality, HVDC, STATCOM, shunt active power filters, and renewable energy sources. It is observed from the literature that there is a research gap in the implementation of MMC for D-STATCOM. Hence, in this work the MMC based D-STATCOM using PD PWM is considered. The contribution of this work includes the adoption of the MMC as D-STATCOM for the improvement of power quality (active power, reactive power, power factor, and TDH). The proposed work is compared with the standard two-level inverter and with HCC PWM. From the results, it is observed that the proposed five-level MMC based D-STATCOM using PDPWM over performed the standard inverters.

VI. CONCLUSION

The PD PWM control method for reactive power, harmonics, and DC voltage balancing in MMC-based D-STATCOM performance has been analyzed in this paper. It has been determined that the effectiveness of MMC-D-STATCOM when utilizing PD PWM-based control is satisfactory. Harmonics, reactive power, and DC voltage balance, among other power quality issues, have been corrected with the help of MMC-DSTATCOM. The THD in the supply current was decreased to 4.91% from 24.43%. Following the application of the compensation, the total harmonic distortio of the supply current was brought down to an acceptable level according to the criteria outlined in the IEEE-519 standard [19-25]. This improvement in power quality was made possible by the MMC-DS-TATCOM. The self-supported DC-link voltage of MMC-DSTATCOM is also referenced.

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