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D-STATCOM Pulse Selection and Transformer Configuration for Harmonic Elimination

***Abstract**. The sensitive industrial loads and critical commercial operations suffer from harmonics problems which can cost significant loss per incident based on process down-time, loss production, idle work forces and other factors. To overcome such problems, utility companies have made efforts to improve the quality and reliability of their electric power by introducing distribution static compensator (D-STATCOM). However, up to now, many research are going on D-STATCOM control scheme, suitable pulse and transformer design, dc capacitance effect and involvement with many power quality problems. This paper deals with the modelling and simulations of D-STATCOM model focus with the pulse selection, transformer design configuration and test distribution system. The issue of harmonics in the D-STATCOM is addressed by considering a 24-pulse so as to eliminate the generated harmonics. The harmonics eliminating performance of the D-STATCOM in 12-pulse, 24-pulse and 48-pulse are also investigated.*

***Streszczenie**. W artykule opisano budowę modelu i symulacje kompensatora statycznego D-STATCOM. Przedstawiono zagadnienie liczby pulsów, konfiguracji transformatora oraz przeprowadzono testy systemu energetycznego. Analizie poddano zagadnienie eliminacji wyższych harmonicznych w układach 12-, 24- oraz 48-pulsowym. (**Dobór liczby pulsów i konfiguracji transformatora kompensatora D-STATCOM – eliminacja wyższych harmonicznych**)*

Keywords: D-STATCOM, Pulse selection, harmonics, inverter transformer, power quality
Słowa kluczowe: D-STATCOM, wybór liczby pulsów, harmoniczne, transformator falownikowy, jakość energii.

Introduction

D-STATCOM is a solid state, three phase inverter based power controller which is connected in shunt to a distribution feeder through a coupling transfer that matches the inverter ac output voltage to the distribution system voltage [1]. Thus, D-STATCOM is used to protect the distribution system from power quality disturbances [2]. The main components of the D-STATCOM are the inverter using either GTO or IGBT, dc capacitor, coupling transformer and control system [3]. It can be regarded as an active energy-exchanging device because it utilizes the passive energy storage component to realize the energy storing and exchanging and the switches to control the reactive power flow between different phases of a distribution system [4-6]. The reactive power provided by the D-STATCOM is either capacitive or inductive depending on whether the magnitude of the D-STATCOM output voltage is larger or smaller than the magnitude of the system voltage [7].

In recent years, D-STATCOM has been extensively studied in which many papers in the literature have discussed its theory, modelling, control and applications (4, 8-10). Design and performance evaluation of a D-STATCOM requires extensive analysis of the interaction between the D-STATCOM and the associated distribution system. There are two types of D-STATCOM models, namely, the conventional D-STATCOM and PWM D-STATCOM. The conventional D-STATCOM is controlled at low switching fundamental frequency of the inverter based on the control of the phase angle of the fundamental switching pattern [11]. However, the PWM D-STATCOM assumes the inverter switches at high frequency based on PWM switching technique where magnitude and phase of the D-STATCOM output voltage are controlled independently [12-16]. An alternative method to reduce the low-order harmonic content of the D-STATCOM is proposed by Singh et al. (2009) using hysteresis current control which performed better compared to the conventional D-STATCOM [17]. Holmes & McGrath (2001) introduced a carrier based PWM control strategy used for inverter control to eliminate harmonic in the multi-level cascaded inverter system through carrier phase shifting [18].

In the operation of D-STATCOM, the problem of harmonics generated by the device has been addressed by Mohaddes et al. (2001) and Dong et al. (2001) [4, 7]. Methods for reducing harmonics produced by D-STATCOM are by means of PWM switching technique and filters. Most of the models have been presented in the literature are the 6-pulse and the 12-pulse D-STATCOM [3]. In this paper, the development of a D-STATCOM model with focus on the pulse selection, transformer design configuration and test distribution system is implemented. The issue of harmonics in the D-STATCOM is addressed by considering a 24-pulse so as to eliminate the generated harmonics. The harmonics eliminating performance of the D-STATCOM in 12-pulse, 24-pulse and 48-pulse are also investigated.

D-STATCOM Pulse Selection

In the selection of the inverter pulse number, it is noted that the harmonic components of the 12-pulse inverter output voltage may not be acceptable in many applications. Thus, an inverter with a higher pulse output voltage has to be considered. With high-speed sensing and fast turn-off capability of switching devices, parallel connection of large number of inverters is quite feasible in the D-STATCOM design. Considering switching loss and in particular to satisfy the harmonic requirements of the D-STATCOM, the 24-pulse inverter is selected in the D-STATCOM design. The four of the 6-pulse inverters are combined to form the 24-pulse inverters as shown in Fig. 1. In this arrangement, the output voltages from the four, 6-pulse inverters (I, II, III and IV) are combined using four single-phase transformers. The phase shift between the two consecutive 6-pulse inverters is calculated and found to be 15 degrees by using the phase shift displacement angle formula which is given by *2π/6m*, where *m* is the total number of the 6-pulse inverters used.

Thus, the fundamental voltage phasors of I, II, III and IV inverters are shifted by 0^0, 15^0, 30^0 and 45^0, respectively. Combining all the four, 6-pulse inverters output voltages, a 24-pulse inverter output voltage can be obtained in which the instantaneous D-STATCOM output voltage for phase *a* can be calculated as,

$$V_a = a_1 V_{a1\,y} + a_2 \frac{V_{a2\,\Delta}}{\sqrt{3}} + a_3 V_{a3\,y} + a_4 \frac{V_{a4\,\Delta}}{\sqrt{3}} \quad (1)$$

where, a_1, a_2, a_3, a_4 are the voltage ratios of the corresponding transformers, $V_{a2\,\Delta}/\sqrt{3}$ and $V_{a4\,\Delta}/\sqrt{3}$ are the phase *a* voltages for inverters 2 and 4, $V_{a1\,Y}, V_{a3\,Y}$

phase *a* voltages for inverters 1 and 3. The D-STATCOM output voltages for phase *b* and *c* can be similarly written as (1) using the respective phase *b* and *c* voltages of the inverters.

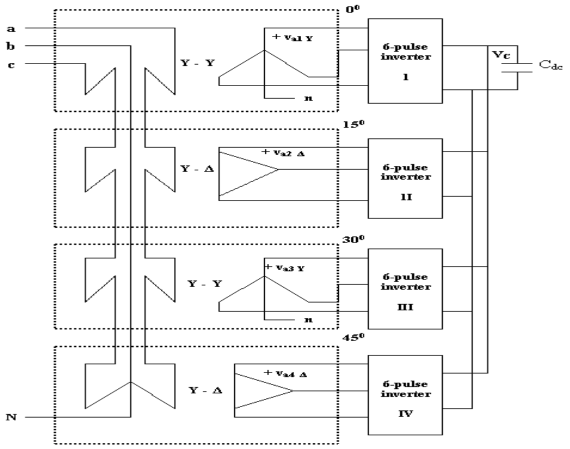

Fig. 1. The 24-pulse D-STATCOM inverter arrangement

Transformer Configuration

The 24-pulse inverter arrangement utilizes four transformers with their primaries connected in series as shown in Fig. 2. There are four, 6-pulse inverters which are identical to make up the 24-pulse inverter arrangement in which all the GTO switches and diodes of the inverters have the same voltage and current ratings. The 6-pulse inverters are connected in parallel so as to keep the voltage on the dc side as low as possible and to optimize the utilization of the dc side capacitor. Two of the inverters are connected to the system through the Y-Y connected transformers and the other two of the inverters are connected via the Y-Δ connected transformers [1]. The primary windings of all the twelve single-pulse transformers are connected in series in order to avoid harmonic circulating current and to minimize its size and costs [19]. The leakage reactance's of the transformers are kept low so as to prevent a large voltage drop. The step-down transformers that are used in the simulation are 22/4.6 kV transformers and the leakage reactance of each transformer is 0.01 per unit. All the four, 6-pulse inverters are connected in parallel on the same dc bus to form the 24-pulse inverter. This is to keep the voltage on the dc side as low as possible and to optimize the utilization of the dc side capacitor. In the parallel connection, V_{dc} will be the same for each inverter. However, in the series connection, V_{dc} will be different for each inverter and an additional control is needed to ensure that each inverter has equal voltage.

In this section, the 24-pulse D-STATCOM simulation model which has been designed using the components in the PSCAD/EMTDC program is presented. In the development of the simulation model, considerations have been made on the selection of inverter pulse number and capacitor sizing. These considerations are discussed in the following sections but first the designed D-STATCOM simulation model is described as shown in Figure 2. The D-STATCOM simulation model is a two levels, three phase, 24-pulse model consisting of twenty-four self-commutated GTO switches with anti-parallel diodes. This valve combination and its capability to act as a rectifier or as an inverter with instantaneous current flows in positive or negative direction, respectively, is the basic voltage source converter concept. In this simulation, the GTOs are selected for the design of the voltage source converter because it is more suitable for high power applications in which it can withstand up to 6 kV, 6 kA with a maximum switching frequency of 10 kHz and switching time of 15 μs. Furthermore, in this simulation, the test system considered is the 22 kV distribution systems with 1.2 MVA load. The advantages of GTO compared to IGBT are that it has high voltage blocking capability, high ratio of peak average current (typically 10:1), high on-state gain (anode/gate current, typically 600 A) and a pulsed gate signal of short duration.

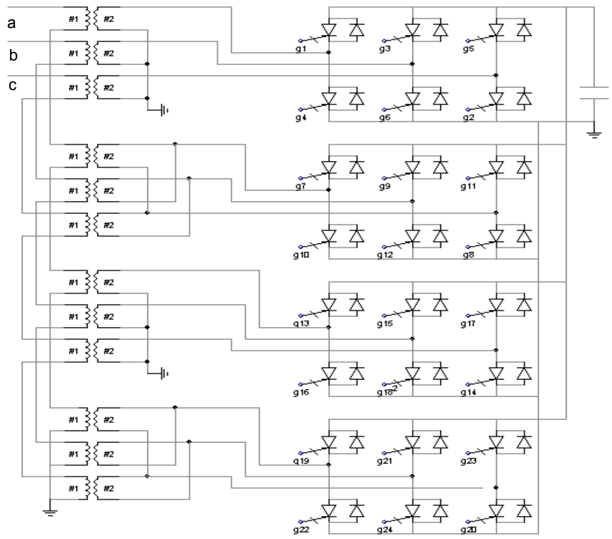

Fig. 2. The three-phase 24-pulse D-STATCOM model

D-STATCOM in a Distribution System

A simplified distribution system model has been chosen as a test system for investigating the performance of the D-STATCOM. The system considers several static and induction motor loads, which are connected to a common load bus. The detailed load characteristics of various ratings are given in Table 1. The D-STATCOM in the test distribution system has been implemented in PSCAD/EMTDC simulation.

Table 1. Loads in the test distribution system

Load	Type	Rating	Parameters	
			R (Ω)	L (H
Load 1	RL	1.2 MVA, 0.90 P.F.	363.33	0.46
Load 2	RL	0.5 MVA, 0.95 P.F.	871.21	1.119
Load 3	IM	1600 H P, 50 Hz	---	---
Load 4	IM	1600 H P, 50 Hz	---	---
Load 5	RL	1.2 MVA, 0.90 P.F.	363.33	0.46

Results and Discussion

To evaluate the performance of the D-STATCOM, it is simulated using the PSCAD/EMTDC transient simulation program. The D-STATCOM is connected to a 22 kV distribution system with three static loads and two induction motor loads, as shown in Figure 3. There are twelve single-phase transformers with each rated at 5 MVA, 22/4.16 kV and a leakage reactance of 0.01 p.u. Simulations were carried out to illustrate the use of the D-STATCOM for harmonic elimination. Prior to these simulations, D-STATCOM design considerations were investigated with respect to the selection of the pulse number and the transformer configuration.

To select the optimum pulse number of the D-STATCOM inverter, simulations are first carried out using the 12-pulse, 24-pulse and 48-pulse inverters. The selection is made by investigating the effect of the pulse number of the inverter on the harmonics generated by the D-STATCOM. Fig. 3 shows the individual voltage harmonic contents generated by the 12-pulse, 24-pulse and 48-pulse inverters, respectively. It is noted that the fundamental component is the same regardless of the pulse number. It can be seen that voltage harmonics are reduced with the higher pulse inverter as compared to the lower pulse inverter due to phase displacement angle among the inverters. Therefore, harmonics can be reduced when using higher pulse number inverter.

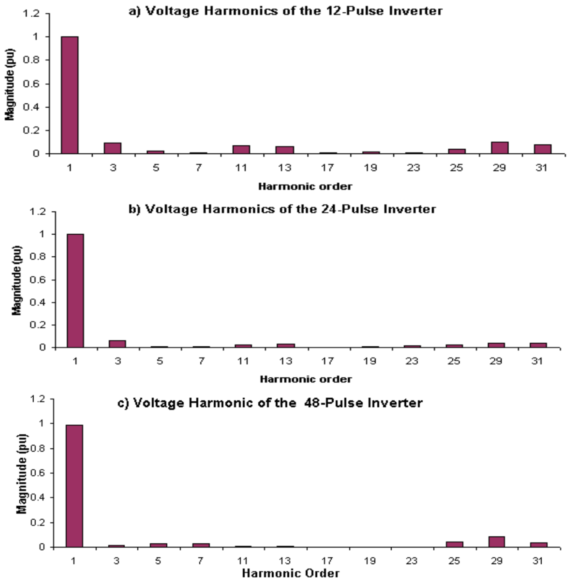

Fig. 3. Voltage harmonic content a) 12-pulse b) 24-pulse c) 48-pulse inverters

In terms of the total harmonic distortion (THD), results in Figure 5 shows that the 12-pulse, 24-pulse and the 48-pulse inverters generate 15.5%, 6.5% and 8.4% of THD, respectively. Due to high frequency switching losses, even the 24-pulse and the 48-pulse inverters have generated THD which are higher than the acceptable level of 5% [20]. Therefore, filtering is indispensable so as to eliminate the harmonics generated by the D-STATCOM. From the THD results, it is noted that in the case of the 48-pulse inverter, a bigger passive filter is needed to eliminate the generated harmonics as compared to the 24-pulse inverter. Thus, based on the harmonic results and considering the size of the required passive filter to reduce the THD, the 24-pulse inverter is selected as the optimum pulse number of the D-STATCOM. The 24-pulse D-STATCOM is thus used as a basis in the D-STATCOM simulation model.

Several different approaches have been proposed for reducing the harmonics produced by the D-STATCOM. In this simulation, a passive filter is connected at the point of common coupling to the distribution system, which is at the primary side of the transformer. To illustrate the effect of using an LC passive filter, similar D-STATCOM simulation as described in section 5.1.4 were carried out and the THD of the system without and with the filter inserted into the system are recorded. Figures 5.4 (a) and (b) show the THD of the system without and with the filter, respectively. From the simulation results, it can be seen that with the filter connected, the harmonics are suppressed and the THD of the system is reduced to 0.65% from 6.4%. The THD of 0.65% is far below the value of the IEEE standard THD limit of 5%.

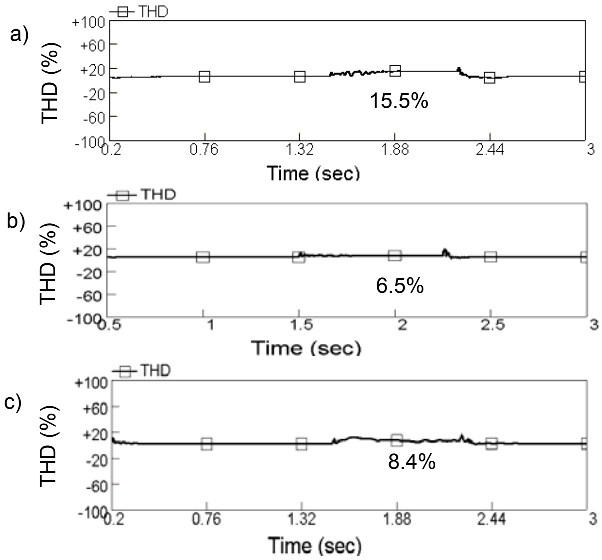

Fig. 5. Total harmonic distortion a) 12-pulse b) 24-pulse c) 48-pulse D-STATCOM

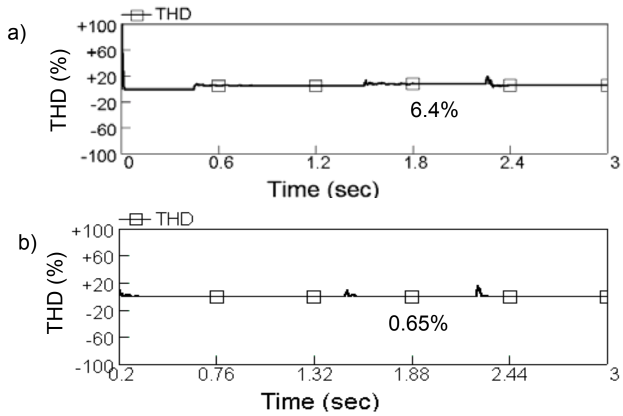

Fig. 4 Total harmonic distortion a) without filter b) with filter

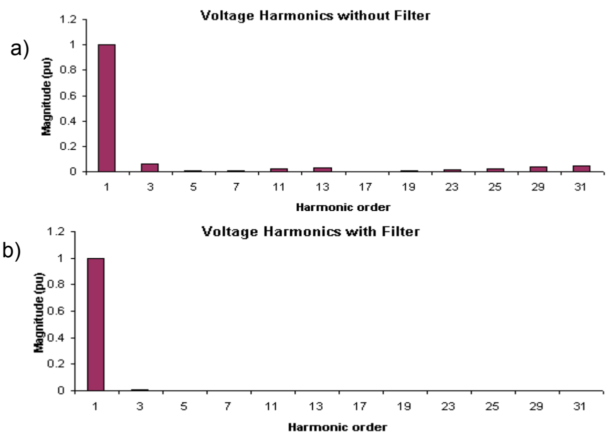

Fig. 5 Voltage harmonic content a) without filter b) with filter

To illustrate further the effect of using a passive filter in eliminating harmonics in the system with the D-STATCOM, individual voltage harmonic contents are obtained by using Fast Fourier Transform analysis on the measured voltage. Figure 5.5 shows the results of the individual voltage harmonic contents. With the filter connected in the system, it can be seen that the individual voltage harmonic contents are reduced to approximately zero. However, without the filter some of the higher order harmonics such as 3rd, 11th, 13th, 25th, 29th and 31st have harmonic distortion values of 6.0%, 2.5%, 3.0%, 2.0%, 3.7% and 4.3%, respectively. These values exceed the 3rd, 11th, 13th, 25th, 29th and 31st harmonic distortion limits of 4.0%, 2.0%, 2.0%, 0.6%, 0.6% and 0.6.% , respectively (IEEE 519-1992). The size of the passive filter considered in the simulation are L = 0.2 H and C = 25 μF.

Conclusion

The D-STATCOM model, pulse number selection and transformer configuration were developed using the PSCAD/EMTDC electromagnetic transient program. The improved two level 24-pulse D-STATCOM models are designed for harmonic elimination in a test distribution system. The 24-pulse D-STATCOM simulation models are considered to give better performance than that of 12-pulse and the 48-pulse simulation models in terms of harmonic generation. The pulse number of the D-STATCOM is investigated on the issue especially in harmonic elimination. This study has been made the suitable pulse selection on the effectiveness of the D-STATCOM in eliminating harmonics in a test distribution system. The improved simulation models, analyses on inverter pulse-number selection, transformer configuration have been addressed and provided a better understanding of the compatibility between the D-STATCOM, the distribution system and loads. Thus, this model can be used as a basis for the development of prototype D-STATCOM.

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