Auto tuning of PI Gains using Cuttlefish Optimization for DC Link Voltage Control in a 5-level HB MMC D-STATCOM

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Received: 19 September 2023 | Revised: 6 October 2023 | Accepted: 7 October 2023

 DOI: https://doi.org/10.48084/etasr.6413

ABSTRACT

The performance of a Half Bridge (HB) Modular Multilevel Converter (MMC) for D-STATCOM application is studied in this article. For the control of MMC switches, the Carrier-Based (CB) Pulse Width Modulation (PWM) scheme has been selected as the appropriate method. There are two types of CB PWM schemes such as phase shift and level shift. Phase Disposition (PD), Phase Opposition Disposition (POD), and Alternate Phase Opposite Disposition (APOD) are the three different types of PWM that are used in level shifts. The PD CB PWM is projected in this work due to its simplicity and accuracy. The conventional PI Controller (PIC) has its disadvantages, including that it is time-consuming and comes with complexity in the estimation of gain values. Hence, the Cuttlefish Optimization Scheme (COS) is proposed for the online tuning of the PI gain values. The verification of performance parameters, including active power, reactive power, DC voltage balance, and Total Harmonic Distortion (THD), is effectively conducted using the COS method and subsequently compared with the conventional PIC. The suggested research is executed using the Matlab/Simulink software package.

Keywords-carrier-based PWM; D-STATCOM; half bridge; THD; phase disposition; PI; COS; MMC

I. INTRODUCTION

An electric power system refers to a complex network comprising diverse electrical components that are strategically installed to facilitate the generation, transmission, distribution, and utilization of electrical power [1]. The term "distribution system" denotes to the conduit that is developed in the process of delivering electricity to the final users of the product. Enhanced power quality is the engine that propels the modern industrial sector of today's economy. Over the last decade, there has been a discernible increase in the amount of awareness that consumers have regarding the significance of a dependable power supply [2]. A Voltage Source Converter (VSC) is what makes up DSTATCOM. It produces the required capacitive and inductive reactive power. The control mechanism exhibits a high degree of responsiveness, enabling it to promptly address system requirements. Additionally, it possesses the capability to provide an ample amount of reactive power compensation to the interconnected system [3]. Before the development of DTATCOM, it was common practice to use systems based on thyristors for reactive power compensation and mitigating voltage flicker caused by arc furnace loads. This was done before the invention of DTATCOM. On the other hand, passive devices have a number of drawbacks, including a fixed compensation, large size, the possibility of resonance, and so on. As a result, new compensators, such as DSTATCOM, are becoming increasingly popular as a solution to power quality issues. Due to the inherent non-linearity of power electronic devices, these devices have a tendency to draw reactive power and harmonics from the power supply [4]. In certain instances, they may also induce imbalance within three-phase systems and result in the generation of unnecessary neutral currents. Due to the added harmonics, the reactive power problem, the imbalance, and the unwarranted neutral currents, the structure's efficiency is reduced, and its power factor is low. Both these problems are caused by excessive neutral currents. The emergence of power quality as a significant concern can be attributed to the increasing intolerance of various loads [5]. The primary focus of power quality pertains to matters related to the consistent maintenance of a stable voltage at the Point of Common Coupling (PCC) across different circulation voltage stages, regardless of voltage instabilities. Additionally, power quality involves the maintenance of a power factor that is in close proximity to unity, prevention of upward transmission of current unbalances from different circulation levels, and mitigation of voltage and current harmonics within the structure. All these issues are covered under the umbrella term "harmonics reduction." The fact that multilevel inverters do not necessitate the use of a coupling transformer [6] in settings that involve medium voltage and the fact that they have a comparatively little harmonic current contented are two of the furthermost significant advantages that these devices provide. In the traditional method, the D-STATCOM application is handled by utilizing two level converters. Conventional two-level inverters are producing more THD in grid current. Hence the Modular Multilevel Converter (MMC) -based D-STATCOM is proposed in this work. Conventionally, PIC and Fuzzy Logic Controllers have been implemented for the DC voltage balance in Multi-Level Inverters (MLI). The traditional method of learning the gain values of a PIC, which relies on trial and error, is both time consuming and complex [7]. Hence, COS is adopted in this work for the automatic selection of the PI gain values.

II. METHODOLOGY

The proposed configuration is depicted in Figure 1. It consists of an electric source or grid, non-linear loads, and voltage source-based DSTATCOM. Half Bridge (HB) based MMC is adopted as the voltage source converter as shown in Figures 2 and 3. The HB modules required are calculated as N + 1 for the N-level. For 5-level output, 4+1=5 means that four sub modules are required.

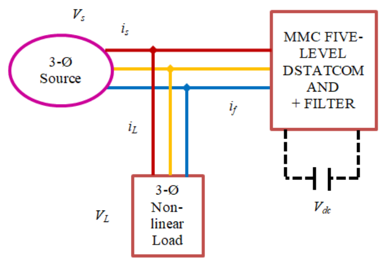

Fig. 1. The proposed configuration.

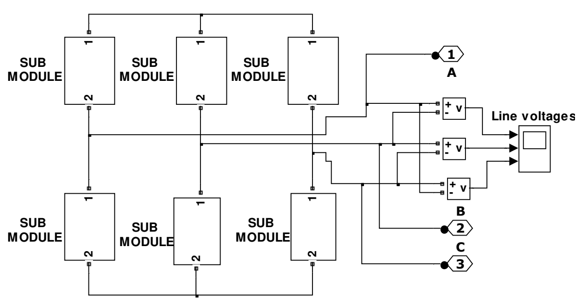

Fig. 2. Schematic diagram of the MMC.

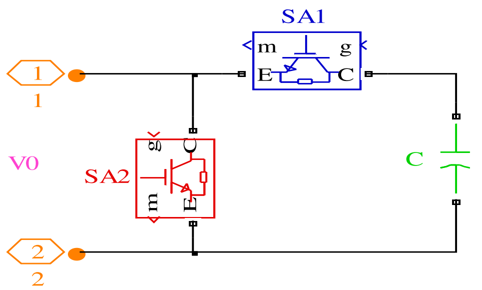

Fig. 3. HB sub module of the MMC.

TABLE I. HB SM SWITCHING

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

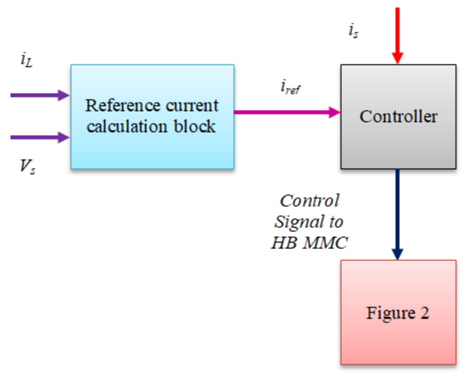

Fig. 4. Schematic representation of the MMC control block.

The switching table is depicted in Table I. The control block diagram of the MMC is illustrated in Figure 4 [8]. It consists of a reference current generator and DC link voltage termed as MMC capacitor controller. The mathematical equations for reference current calculation block are presented below. The axes *a*, *b*, and *c* are all located on the same plane, but they are spaced apart from one another by a distance equal to two-thirds of the *a*-*b*-*c* coordinates. The axes denoted by α and β are examples of orthogonal coordinates.

$$\begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} = \sqrt{0.667} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & 0.866 & -0.866 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} = \sqrt{0.667} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & 0.866 & -0.866 \end{bmatrix} \quad (2)$$

The computation of active power (p) and reactive power (q) can be attained by utilizing the equation derived from the *α*–*β* coordinate system. [9]:

$$p = V_{s\alpha} i_{L\alpha} + V_{s\beta} i_{L\beta} \quad (3)$$

$$q = -V_{s\beta} i_{L\alpha} + V_{s\alpha} i_{L\beta} \quad (4)$$

Moreover, the variables p and q can be represented as matrices in the following manner:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_{s\alpha} & V_{s\beta} \\ -V_{s\beta} & V_{s\alpha} \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \quad (5)$$

There are two parts that make up the instantaneous active power, which is denoted by the symbol p: the oscillatory (AC) component $\tilde{p}$ and the average (DC) component $\bar{p}$. The oscillatory component $\tilde{q}$ and the average (DC) component $\bar{q}$ are the two parts that make up the reactive power q, which also has two parts [9]. The variables p and q are expressed by:

$$p = \bar{p} + \tilde{p} \quad (6)$$

$$q = \bar{q} + \tilde{q} \quad (7)$$

Given that the source exclusively provides the DC component of the active power, it is only necessary to consider the average component $\bar{p}$ in the calculation of the required reference current value, while maintaining the reactive power q at a value of zero. The required reference currents on the source side i_{ref} based on the α–β coordinates are $i_\alpha^*$and i_β^*:

$$\begin{bmatrix} i_{L\alpha}^* \\ i_{L\beta}^* \end{bmatrix} = \frac{1}{V_{s\alpha}^2 + V_{s\beta}^2} \begin{bmatrix} V_{s\alpha} & -V_{s\beta} \\ V_{s\beta} & V_{s\alpha} \end{bmatrix} \begin{bmatrix} \bar{p} \\ 0 \end{bmatrix} \quad (8)$$

In fact, on the load side, the reference current i_{ref} is determined using inverse Clark's transformation. It is defined as [9]:

$$\begin{bmatrix} i_{refR} \\ i_{refY} \\ i_{refB} \end{bmatrix} = \sqrt{0.667} \begin{bmatrix} 0.707 & 1 & 0 \\ 0.707 & -0.707 & 0.866 \\ 0.707 & -0.707 & -0.866 \end{bmatrix} \begin{bmatrix} i_0^* \\ i_{L\alpha}^* \\ i_{L\beta}^* \end{bmatrix} \quad (9)$$

The zero-sequence part of this equation is denoted by the symbol i_0*. In this work, the value of i_0^* is 0. The generated reference signal is presented in Figure 5.

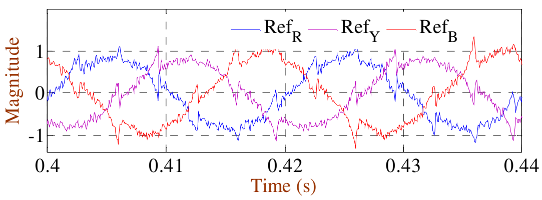

Fig. 5. Generated reference signal.

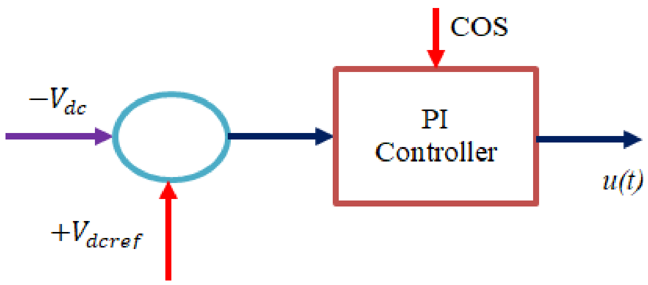

Fig. 6. PIC using COA.

Figure 6 depicts the MMC capacitor voltage controller using a COS tuned PIC. Cuttlefish Optimization Algorithm (COA), is a bio-inspired metaheuristic set of rules [10] that was designed to replicate the color-changing behavior of cuttlefish. COA or Cuttlefish Optimization Scheme (COS), is a nature-inspired algorithm for optimization that imitates the hunting behavior of cuttlefish [11-12]. It can be used to design PI controllers for various control systems. The steps of using the COA to design a PIC are:

Step 1: Define the control system.

Step 2: Define an objective function that can be used to quantify how well the control system is performing [13]. In most cases, this entails achieving the lowest possible value for a cost function, such as the Integral of the Squared Error (ISE) or the Integral of the Absolute Error (IAE), or some other appropriate performance criterion.

Step 3: Represent the PIC in a way that can be optimized using the COA. Proportional gain (K_p), integral time (T_i), or integral gain (K_i) are typically used to parameterize PICs. These parameters will be optimized by the algorithm.

Step 4: Initialize a population of cuttlefish individuals. Each individual corresponds to a potential solution in the search space of the controller parameters (K_p and T_i/K_i). It can randomly initialize the cuttlefish positions within a predefined range.

Step 5: Estimate the suitability of each cuttlefish in the population by applying its corresponding PIC to the control system and computing the objective function value.

Step 6: Main loops

Step 7: Once the algorithm terminates, select the best-performing cuttlefish (controller parameters) as the optimized PIC for your system.

Step 8: Implement the optimized PIC in the control system and evaluate its performance through simulation or experimentation. Make any necessary adjustments based on real-world results.

III. SIMULATION RESULT ANALYSIS

The proposed configuration was simulated and the results are elaborated in this section. The simulation result analysis is made in two cases. In first case, the MMC [14-15], the capacitor voltage is controlled by the conventional PIC [16-19] using the trial and error method. The corresponding result waveforms are presented in Figure 7. The MMC capacitor voltage controller [20] takes more time to reach the steady state due to the inaccuracy in selection of K_p and K_i gains of the PIC. The THD is recorded as 4.91%. The settling time of the DC voltage link is 1.2 s as shown in Figure 7(g). Active and reactive power [21-25] values are 6.233 W and 1.160 Var. The MMC capacitor voltage controller achieved the reference voltage of 700 V at t = 1.2 s. The simulation specifications are listed in Table II.

TABLE II. VALUES CONSIDERED FOR SIMULATION

Description	Value
3-phase supply/grid voltage, L_s and R_s	415 V (rms), 200 mH and 0.01 Ω
Rectifier load	3 phase diode bridge with RL load
Switching frequency	5000 Hz
V_{dcref}	700 V
Capacitor, C	3300 μF

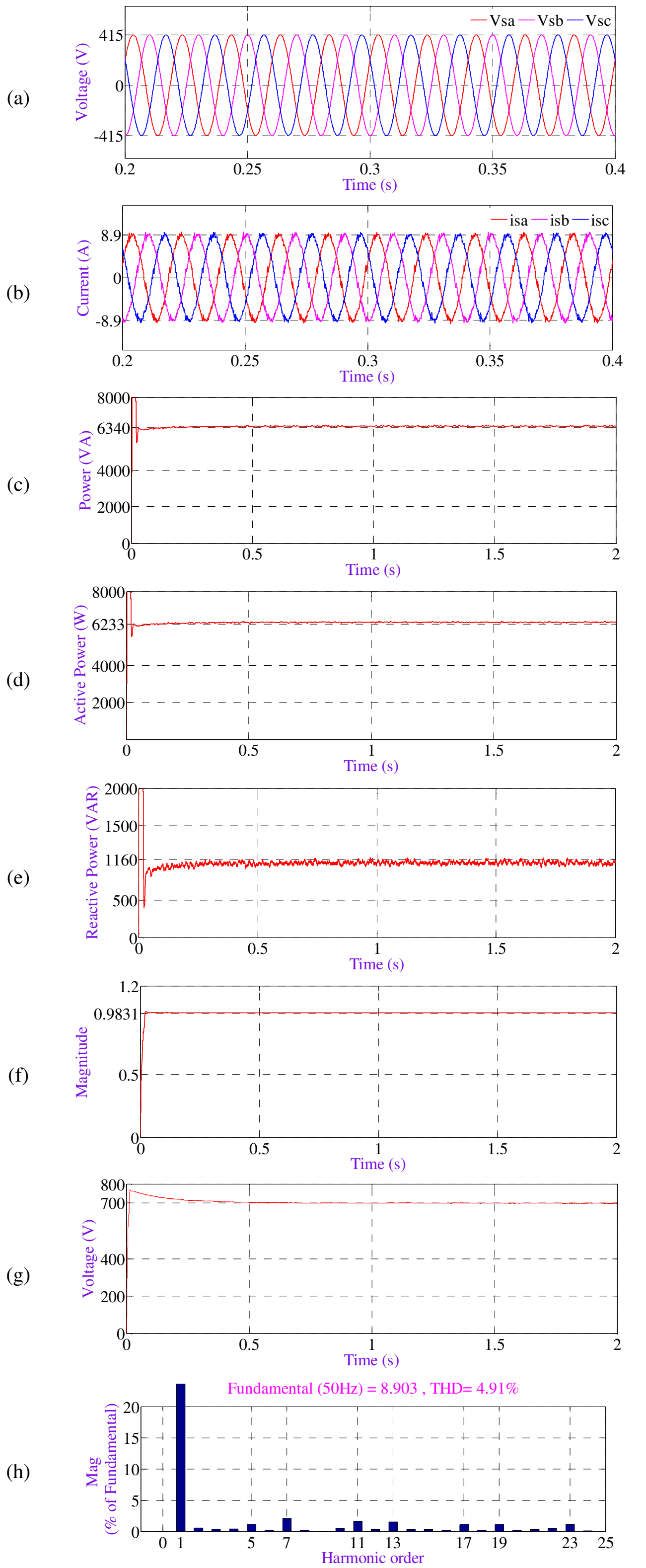

Fig. 7. Response waveforms using five-level HBMMC-DSTATCOM using the conventional PIC: (a) Source voltage, (b) source current, (c) apparent power, (d) active power, (e) reactive power, (f) power factor, (g) DC voltage, (h) harmonic spectrum of the source current.

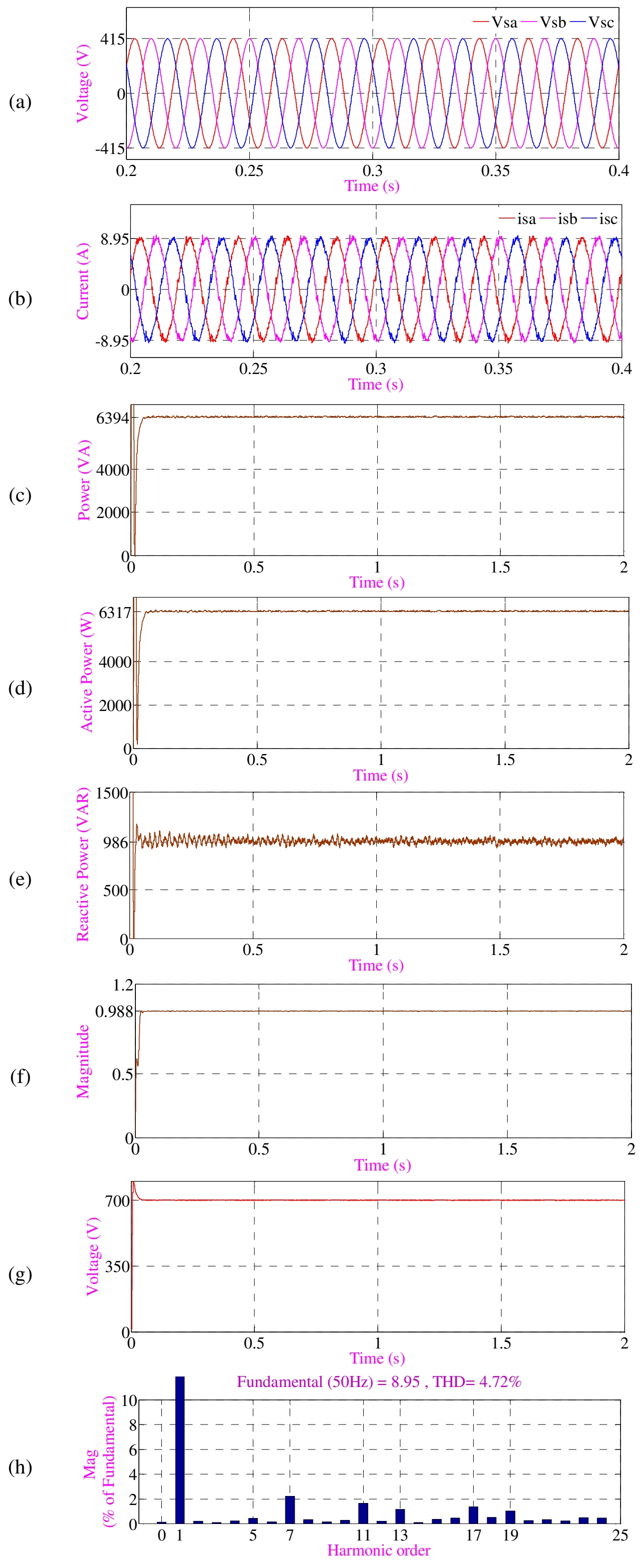

Fig. 8. Response waveforms using five-level HBMMC-DSTATCOM with COA: (a) Source voltage, (b) source current, (c) apparent power, (d) active power, (e) reactive power, (f) power factor, (g) DC voltage, (h) harmonic spectrum of the source current.

In the second case, the MMC capacitor voltage is controlled by the PIC with COA. The corresponding result waveforms are presented in Figure 8. The MMC capacitor voltage controller requires less time to reach the steady state due to the accuracy in the selection of K_p and K_i gains of the PIC. The recorded THD is 4.72%. The settling time of the DC voltage link is 0.04 s as shown in Figure 8(g). The observed active and reactive powers are as 6.317 W and 986 Var. The MMC capacitor voltage controller achieved the reference voltage of 700 V at t = 0.04 s. The performance comparison of the produced parameters using the conventional PIC and the COS-tuned PIC can be seen in Table III.

TABLE III. PERFORMANCE COMPARISON

Parameter	PIC	PIC trained by COA
S (VA)	6,340	6,394
P (W)	6,233	6,317
Q (VAR)	1,160	986
PF	0.9831	0.988
DC voltage settling time (s)	1.2	0.04
i_{sa} (A)	8.903	8.95
Source current %THD	4.91	4.72

IV. DISCUSSION

MMCs have become increasingly popular during the recent years in many power quality applications, including DSTATCOM, active power filters, solar panels, and wind energy conversion systems. There is a gap regarding ways to best implement MMC for D-STATCOM using optimization techniques. As a result, the MMC-based D-STATCOM that uses COS is taken into consideration in this work. The implementation of the MMC as D-STATCOM is one of the contributions made by this body of work towards the enhancement of power quality metrics. The performance level of the proposed controller is analyzed and contrasted with that of the traditional PIC. The results show that the proposed five-level MMC-based D-STATCOM that makes use of COA has superior performance when compared with the traditional PIC.

V. CONCLUSION

The principles of the Distribution Static Compensator (D-STATCOM) based on the Modular Multilevel Converter (MMC) were presented in this paper and the efficacy of the control structure was thoroughly examined. This study introduces a method for achieving capacitor voltage balancing in a Modular Multilevel Converter (MMC) with the aim of reducing Total Harmonic Distortion (THD) and reactive power in a five-level D-STATCOM based on the MMC technology. The objective of this implementation is to enhance the effectiveness of the algorithm. The effectiveness of the proposed COA-tuned PI controller was proven to be superior to the conventional trial and error method. The settling time of the MMC capacitor voltage has been successfully reduced to 0.04 s using the COA, in comparison to the trial and error method which resulted in a settling time of 1.2 s.

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