A Simulation Study of Crazy-PSO Controller For Direct Matrix Converter

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Abstract

Matrix converter (MC) is an AC-AC converter which provides power flow between AC power supply and the load with different voltage and current requirements. Its relatively small power circuits and simple control structures provide considerable advantages to itself according to the classical AC-AC converter topologies. In this simulation study, optimal control approach based on Crazy Particle Swarm Optimization (CPSO) algorithm is suggested in order to control the Direct Matrix Converter (DMC). The function of CPSO algorithm in the proposed controller is to both minimize the cost function which is the significant part of the optimal controller and also produce the optimum switching states at each switching period. At the end of the study, the results obtained from the DMC system show that the CPSO algorithm based optimal controller provides desired steady-state response towards different load frequency conditions.

1. Introduction

MATRIX converter (MC) is basically an AC-AC converter that converts two different AC powers between each other, which have different voltage and/or current parameters. But there is a significant difference separated it from the classical AC-AC converters: the matrix converters directly convert AC power without any dc-link capacitance or the other large energy storage elements [1]. In addition to this, some significant features such as providing sinusoidal input and output currents, having regeneration capability and having relatively simple and software based control structures are acquired more importance to the MCs [1], [2]. Although the first idea on MC was suggested by Hazeltine's patent in 1923 [3] and the other milestones noted by Friedli and Kolar [4] have been exposed beginning from 1950s, the first practical works start with Venturini and Alesina in 1980 [5], [6]. Venturini suggested the new control method for a single-stage DMC with mxn bidirectional power switches in his study [11]. This type of MC topology directly connects an m-phase voltage source to an n-phase load [2], [5], [6], [7]. Surely, the most useful version of this topology has an input of 3-phase voltage source and an output of 3-phase load as depicted in Fig. 1. Afterwards, a lot of simulations and practical studies about this structure have been realized and published in literature along with developing power electronics and control technologies. These studies are also reviewed in detail by Wheeler et al. [2] and Rodriguez et al. [7]. It can be seen from these reviews that the control technique applied to the MC has high importance in order to produce desired output voltage and current and also stability of the system. In the case of three-phase AC-AC converter, the DMC has nine bidirectional power switches which are separated in threes for each phase as noted above. In each switching period, on-off states of the power switches are changed by the applied control technique so as to produce the output voltage and current with desired amplitude and frequency. Actually, an output voltage of any phase is total of the average values of the instantaneous input phase voltages transferred to the related output by switching the chosen power switches in that period. According to this, overall output voltage of the converter is obtained by appending these average output voltages consecutively. Due to provide this mechanism effectively, different control techniques have been applied to DMC in literature so far [7].

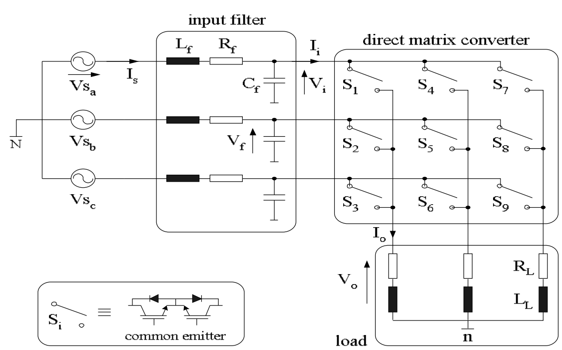


Fig. 1. DMC system topology with RL load.

In literature, the however, the heuristic optimization algorithms such as genetic algorithm, differential evolution, ant colony etc. can offer more powerful methods in order to minimize the cost function for DMC control system as similar to the MPC method. When the DMC control system is evaluated as an optimization problem, these algorithms can be used as an optimal controller by himself and their stochastic search capabilities can increase the robustness of the controller towards different working conditions. As a matter of fact, Hosseini and Babaei applied the Least Mean Square Error (LMSE) method in order to produce the optimum switching states for DMC [8]. After that, Zanchetta obliquely used

Genetic Algorithm in order to automatically tune the PI regulator used in 40 kVA ground power supply including DMC unit controlled with space vector modulation method in 2004 [9], and Villarroel et al. directly applied Fuzzy Logic method for selection of the switching states of DMC system in 2011 [10]. One year after, Sivarani et al. successfully used Fuzzy Logic controller, Particle Swarm Optimization tuned Fuzzy Logic controller and Adaptive Neuro-Fuzzy (ANFIS) controller as a switching strategy in an induction motor driver based on DMC system [11]. At the same year, Ghoni et al. used hybrid PSO (HPSO) algorithm due to the voltage vector selection process of the direct torque control for DMC [12].

This study proposes the heuristic optimization algorithm based control approach to both minimize the cost function and then produce the optimum switching states for a DMC working in different load frequency conditions. Heuristic optimization algorithms optimize the problems iteratively in accordance with given algorithm including significant convergence rules. The probable solutions are converged step by step to the real solution named global optimum in each iteration. The convergence rules can involve some randomness parameters in order to increase the ability to go to the global optimum without falling into the local optimums. This feature mostly improves robustness of the optimization process. In parallel, the aim of using this type of optimization algorithm as a controller in this study is to provide robustness of DMC system for different working conditions such as changing output frequency. For this purpose, the CPSO algorithm which is introduced by Roy and Ghoshal in 2008 is preferred by the author because of its proved superior optimization performance among the other heuristic algorithms [13].

2. Direct Matrix Converter Model

A 3x3 DMC has 9 bidirectional power switches driven with 27 valid switching states as mentioned above. These switching states are generated to avoid both open circuits at the load side and short circuits at the supply side [14]. The switching function for a switch is represented in (1). Also a direct commutation matrix $T(S_i)$ depicted in (2) is composed from (1).

$$S_i = \begin{cases} 1, & S_i \rightarrow \ closed \\ 0, & S_i \rightarrow \ open \end{cases} \tag{1}$$

$$T(S_i^k) = \begin{bmatrix} S_1^k & S_2^k & S_3^k \\ S_4^k & S_5^k & S_6^k \\ S_7^k & S_8^k & S_9^k \end{bmatrix} \tag{2}$$

where i = 1, 2, …, 9. The DMC model is obtained by using (1) and (2).

$$v_0^k = T(S_i^k).v_i^k \tag{3}$$

$$i_i^k = T(S_i^k)^T.i_o^k \tag{4}$$

However, a discrete-time model of DMC is needed in order to minimize the given cost function and last, to produce the best switching states which will be applied to the real DMC as similar to MPC method. Before the discrete-time model is composed, input and output dynamics of the DMC system are represented by the following continuous-time equations according to Fig. 1 [14],

$$v_s(t) = R_f i_s(t) + L_f \frac{di_s(t)}{d(t)} + v_i(t) \tag{5}$$

$$i_s(t) = i_i(t) + C_f \frac{dv_i(t)}{d(t)} \tag{6}$$

$$v_o(t) = R_L i_o(t) + L_L \frac{di_o(t)}{d(t)} \tag{7}$$

The state-space model with the variables vi and is can be also obtained from these equations as depicted below,

$$\begin{bmatrix} \dot{v}_i \\ i_s \end{bmatrix} = A.\begin{bmatrix} v_i \\ i_s \end{bmatrix} + B.\begin{bmatrix} v_s \\ i_i \end{bmatrix} \tag{8}$$

$$A = \begin{bmatrix} 0 & 1/C_f \\ -1/L_f & R_f \end{bmatrix}, B = \begin{bmatrix} 0 & -1/C_f \\ 1/C_f & 0 \end{bmatrix} \tag{9}$$

Consequently, a discrete-time model of DMC represented below can be obtained by using zero-order hold method [14].

$$\begin{bmatrix} v_i^{k+1} \\ i_s^{k+1} \end{bmatrix} = \Phi.\begin{bmatrix} v_i^k \\ i_s^k \end{bmatrix} + \Gamma.\begin{bmatrix} v_s^k \\ i_i^k \end{bmatrix} \tag{10}$$

$$\Phi = \begin{bmatrix} \phi_{11} & \phi_{12} \\ \phi_{21} & \phi_{22} \end{bmatrix} = e^{A.T_s} \tag{11}$$

$$\Gamma = \begin{bmatrix} v_{11} & v_{12} \\ v_{21} & v_{22} \end{bmatrix} = A^{-1}.(\Phi - I_{2x2}).B \tag{12}$$

Also the load current model can be written by using forward Euler approximation in accordance with (7),

$$i_o^{k+1} = d_1.v_o^k + d_2.i_o^k \tag{13}$$

where $d_1=T_s/L_L$ and $d_2=1-T_sR_L/L_L$. In these equations, T_s is named the sampling time [14].

3. CPSO Algorithm Based Optimal Control Approach

The power circuit which is controlled includes a 3-phase DMC fed by 3-phase AC source through LC input filters in order to drive a 3-phase inductive load with different voltage and current requirements. The values of the parameters used in this system are given in appendix. To control this system, CPSO algorithm based optimal controller is suggested in this study. The control structure which is contained DMC model and PSO algorithm is designed based on software as represented in Fig. 2. A function of CPSO algorithm in the controller is to iteratively choose appropriate switching states among 27 valid switching states and apply them to the DMC system.

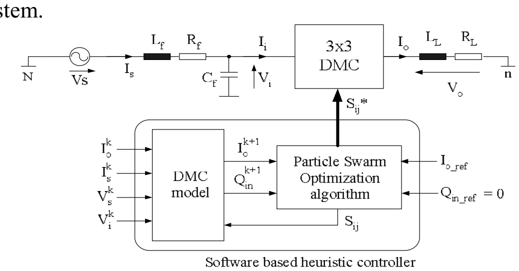


Fig. 2. Structure of the proposed control system.

The CPSO algorithm applies step by step all probable solutions, S_{ij}, in the swarm to the DMC model at each iteration period. Then the DMC model measures the instantaneous output current I_o^k, source current I_s^k, source voltage V_s^k and input voltage V_i^k from the real system and produces the predictions of following output current I_o^{k+1} and the following instantaneous reactive power Q_{in}^{k+1} by using these parameters and references of the output current and instantaneous reactive power. After that, these predictions are transmitted to the CPSO algorithm in order to be able to compute the current values of the cost function, j^{k+1}, represented below.

$$j^{k+1} = (k+1).\left(\left(\Delta i_{o\alpha}^{k+1} + \Delta i_{o\beta}^{k+1}\right) + \Psi.Q_{in}^{k+1}\right) \quad (14)$$

where $\Delta i_{o\alpha}^{k+1}$ and $\Delta i_{o\beta}^{k+1}$ are the absolute values of the output current errors between output current reference, I_{o_ref} and output current prediction, I_o^{k+1} in the α-β frame [10].

$$\Delta i_{o\alpha}^{k+1} = \left| i_{o\alpha}^{*k+1} - i_{o\alpha}^{k+1} \right| \quad (15)$$

$$\Delta i_{o\beta}^{k+1} = \left| i_{o\beta}^{*k+1} - i_{o\beta}^{k+1} \right| \quad (16)$$

Also, the instantaneous reactive power Q_{in}^{k+1} can be computed by the model as represented below [10].

$$Q_{in}^{k+1} = \left| v_{s\alpha}^{k+1}.i_{s\beta}^{k+1} - v_{s\beta}^{k+1}.i_{s\alpha}^{k+1} \right| \quad (17)$$

However, if the input voltage can be considered constant for two sampling period, the equation above can be simplified as below [10].

$$Q_{in}^{k+1} = \left| v_{s\alpha}^{k}.i_{s\beta}^{k+1} - v_{s\beta}^{k}.i_{s\alpha}^{k+1} \right| \quad (18)$$

In addition, Ψ in (14) is the weighting factor changing the effect of the instantaneous reactive power in the formula. PSO algorithm finds the best cost functions at the end of this process. After that, the optimum cost function which has minimum value is chosen among all cost functions. This cost function also indicates the best switching states, S_{ij}^*. Finally, the switching states are sent to the real DMC to produce the desired outputs.

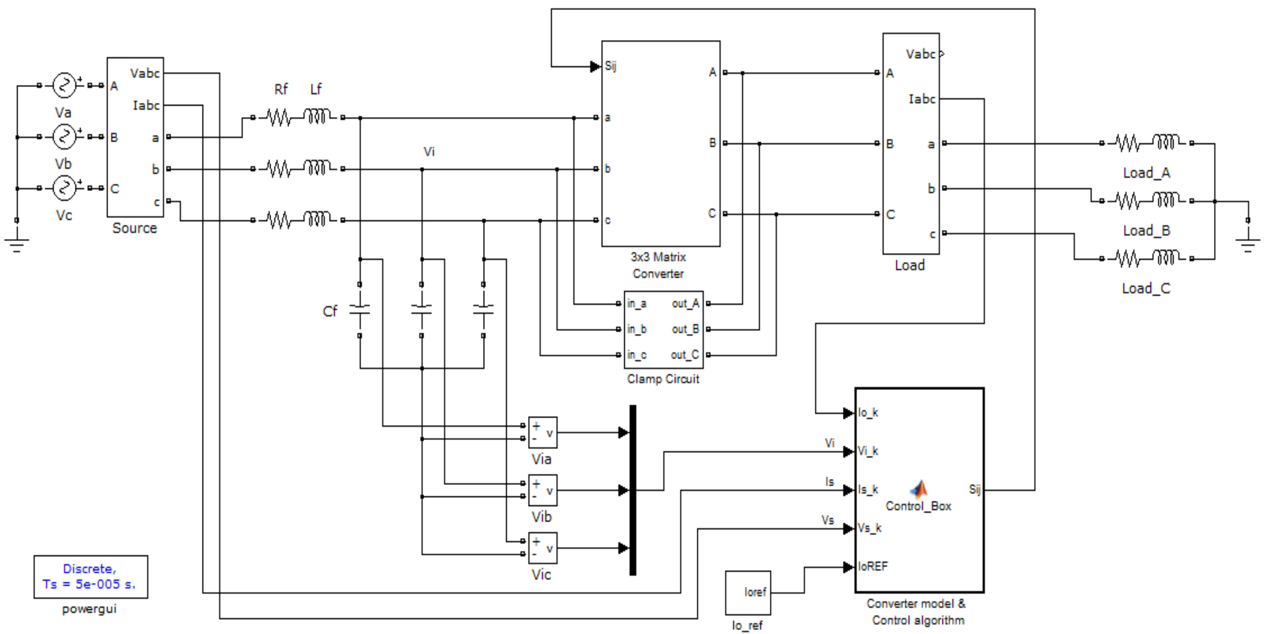


Fig. 3. Block scheme of the control system

4. Simulation Study

The study is implemented on MATLAB/Simulink environment run on the computer including Pentium-T4500 processor and 2 GB RAM . In the study, it is evaluated that the 3-phase DMC is fed by 3-phase balanced AC supply with 200 Vpp phase voltage and provides 5 App, 50 Hz sinuzoidal currents to the 3-phase inductive load including 10 Ω and 15 mH. In addition to this, frequency of the load current can be changed in the range of 5-100 Hz respectively. About ±100% variations of the load frequency is represented in Fig. 4. The Simulink model of the system is also depicted in Fig. 3.

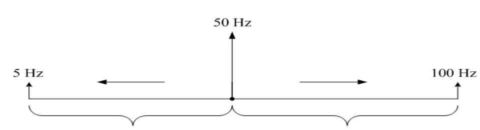


Fig. 4. Output frequency variations

While the 3-phase LC input filter working between AC supply and DMC is used in order to mitigate the high frequency harmonics of the input currents, the clamp circuit works as a protection circuit for the possible voltage spikes under normal and fault conditions of the power system. The software based control box presented in Fig. 3 includes DMC model and PSO algorithm, and it generates the appropriate switching states so as to drive the real DMC. In the CPSO algorithm, the number of particles and iterations are taken 50. Also, c_1 and c_2 constants are taken 2.05. In addition, when the velocities of the particles are computed, the multiplication coefficient used in the computation of maximum boundary of the velocity, v_{max}, is taken 0.655. Particularly, this coefficient is highly important because its lower values decrease the step size of the particles and vice versa. If the step sizes of the particles are lower than the desired values, the particles can not reach the reference currents. In contrast, if the step sizes of the particles are upper than the desired values, the particles exceed the reference currents. The sampling time, T_s, is taken 0.05 ms. T_s is also provide 20 KHz switching frequency for the IGBT switches of the DMC in the simulation.

5. Results and Discussion

The results obtained from the simulations which are realized in case of different current conditions are represented in Fig. 6, 7, 8 and 9. In addition to these, the 200 Vpp, 50 Hz source voltage is also represented in the Fig. 5. The Fig. 6, 7, 8 and 9 are separated into 5 parts including (a) source current, (b) load current, (c) load voltage and (d) FFT analysis of the load current. All analyses apart from Fig. 9 which is the results about 5 Hz load current frequency is realized in the time range of 0.02 s. and 0.08 s. in order to investigate the steady-state response of the DMC system. Fig. 9 is realized in the time range of 0.02 s. and 0.5 s. due to its relatively small frequency. At the end of the simulations, it is seen that the PSO based optimal controller produces the optimum switching states providing the output currents with unity power factor that follow the 5 App load current references within the large frequency range. In addition to this, the source phase currents for all frequency conditions have approximately 23 A peak-to-peak values with their sinusoidal forms. The peak-to-peak values of the output phase voltages are also obtained approximately 100 Vpp. However, when it is investigated the figures of the load currents, the peak values of the phase-A is bigger than those of the other phases. The reason of this situation is commented the tracing error of PSO algorithm. The start point of the phase-A is at zero, but those of the others are different from the zero due to their phase shifts. Because PSO algorithm starts the tracing process at zero point for all phases, the tracing errors will be different for each phase. Furthermore, the best THD% is obtained in case of 50 Hz load frequency. It can be seen that when the load frequency is decreased to 25 Hz and 5 Hz, THD% of the load current increases. In parallel, when the load frequency is increased to 100 Hz, THD% of the load current also increases. There are two reasons for this situation. First of all, the input filter of the DMC has been tuned in order to eliminate the harmonics of 50 Hz load frequency. The second is in the fact that the scaling coefficients of PSO algorithm mentioned in the previous section has been tuned for 50 Hz load frequency as the first application. About ±100% frequency variation is caused the increasing of harmonics and THDs. In spite of these, the steady-state performance of the proposed DMC system controlled with PSO algorithm is sufficient in the range of about ±100% load frequency variation.

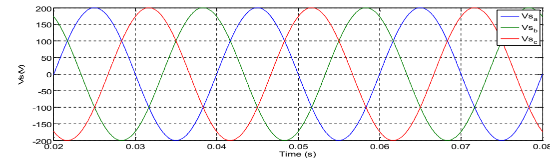


Fig. 5. 200V_{pp}, 50Hz, 3-phase balanced AC source voltage.

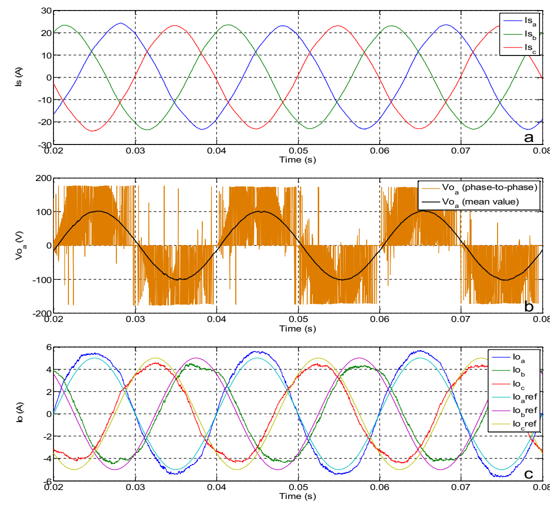


Fig. 6. (a) Source current, (b) load voltage, (c) 5A, 50Hz load current (THD: 7.32%) in the case of balanced AC source.

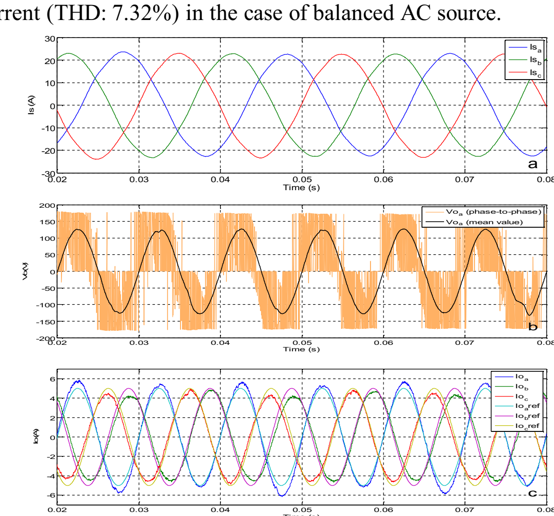
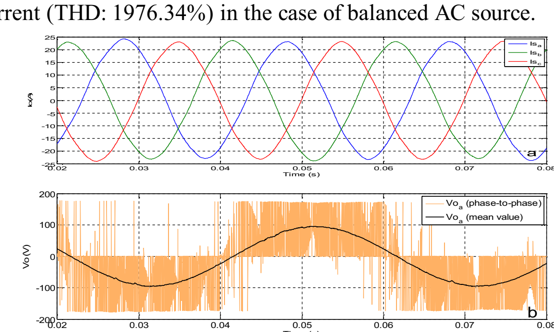


Fig. 7. (a) Source current, (b) load voltage, (c) 5A, 100Hz load current (THD: 1976.34%) in the case of balanced AC source.



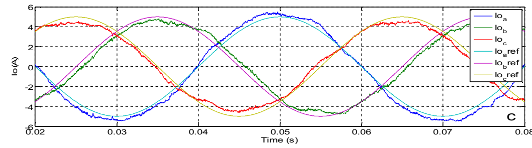


Fig. 8. (a) Source current, (b) load voltage, (c) 5A, 25Hz load current (THD: 31.01%) in the case of balanced AC source.

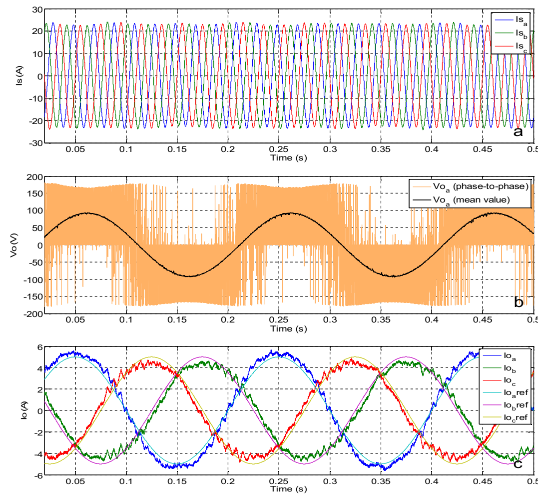


Fig. 9. (a) Source current, (b) load voltage, (c) 5A, 5Hz load current (THD: 67.39%) in the case of balanced AC source.

6. Conclusion

In this simulation study, a swarm intelligence based heuristic optimization algorithm is applied to the DMC system so as to produce optimum switching states for the converter. It is aimed with this study that the heuristic optimization algorithm provides robust control to the DMC system for different working conditions. Actually, the sufficient robust controls are obtained with the chosen CPSO algorithm for different load frequencies changing from 5% to 100% of 50 Hz. However, some undesired results are occurred in the simulations such as increased peak voltage. It is evaluated that these can be accomplished by using hybrid PSO algorithms or the other heuristic algorithms. In addition to these, it is clear that the voltage transfer ratio of the converter is 0.5. The next study will cover the increasing of voltage transfer ratio of the proposed DMC control system.

7. Appendix

Variables	Description	Values
V_s	Source voltage (peak-to-peak)	200 V_{pp}
f_{source}	Source frequency	50 Hz
I_o	Load current (peak-to-peak)	5 A_{pp}
f_o	Load frequency	5, 25, 50, 100 Hz
L_f	Filter inductance	30 mH
C_f	Filter capacitance	150 μF
R_f	Filter resistance	0.5 Ω
L_o	Load inductance	15 mH
R_o	Load resistance	10 Ω
T_s	Sample time (switching time)	50 μs

8. References

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