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Procedia Computer Science 120 (2017) 780–787

Procedia Computer Science

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9th International Conference on Theory and Application of Soft Computing, Computing with Words and Perception, ICSCCW 2017, 24-25 August 2017, Budapest, Hungary

Modular multilevel converter circulating current control using model predictive control combined with genetic algorithm

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Abstract

The modular multilevel converter (MMC) has found various applications in the high voltage industry during the recent years. the MMC consists of several identical submodules (SM). For proper operation of the MMC, balance must be maintained between the upper and lower arm sum capacitor voltages and the ac components of the circulating current must be suppressed. Since the equations which describe the dynamics of the MMC are highly interrelated, the MMC control becomes complicated. In this paper, a control method is proposed to achieve stable and balanced MMC control while reducing the ac components of the circulating current as much as possible. The proposed technique is based on weighted model predictive controlwhich uses genetic algorithm to produce the optimum upper and lower arm insertion indices. The algorithm then produces the corresponding switching patterns by the use of submodule sorting algorithm. The weighting factors were selected based on simulation results. Simulations were carried out on a single-phase MMC with 10 submodules with possible extension to higher levels and phases. Theoretical analysis and simulation results are presented and discussed. They all confirm the effectiveness of the proposed method.

Peer-review under responsibility of the scientific committee of the 9th International Conference on Theory and application of Soft Computing, Computing with Words and Perception.

*Keywords:*Modular multilevel converter; circulating current; model predictive control; genetic algorithm.

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Peer-review under responsibility of the scientific committee of the 9th International Conference on Theory and application of Soft Computing, Computing with Words and Perception.
10.1016/j.procs.2017.11.308

1. Introduction

The multilevel converter technology took a major leap forward by the introduction of the modular multilevel converter in the beginning of the 21st century. Due to its highly-modular structure, the MMC presents several advantages such as better scalability, lower electromagnetic interference (EMI), lower *dv/dt,* and lower switching frequency. These advantages make the MMC suitable for various high-voltage applications such as HVDC transmission systems and high-voltage motor drives.

The MMC is a voltage-source-converter (VSC) and comprises of several identical SMs with capacitors inside. Each SM is considered to be an ac voltage source. By inserting or bypassing each SM, a multilevel voltage can be produced by the converter. In order for the MMC to operate in stable conditions, the voltages of the SM capacitors need to be balanced and the ac components of the circulating current which flows inside the converter should be suppressed in order to reduce the device power ratings and the converter losses. To address these issues, several control methods have been proposed in the literature.

A control method based on injecting a trapezoidal waveform to the common-mode voltage is proposed by Noushak et al. (2017). A 2×2 controller which utilizes 4 SISO controllers for the elimination of the *dq* components of the circulating current was presented by Bahrani et al. (2016). This controller uses the nonparametric model of the converter and is designed using a loop-shaping technique. Konstantinou et al. (2016) proposed a strategy which utilizes the available redundancies in the voltage waveform of an MMC under $2N+1$ modulation. A selective harmonic elimination based control method is proposed by Perez-Basante et al. (2016). Resonant controllers are used for circulating current control by Moranchel et al. (2016). A Quasi-PR controller was proposed by Geng et al. (2016) to extract the dc component of the circulating current and eliminate the second order harmonics. A method using repetitive controllers in $\alpha\beta$ frame was proposed by Moranchel et al. (2016). A technique was also proposed to limit the circulating current within a fixed-band by Chen et al. (2016).

The control systems mentioned above mostly use linear controllers and complex cascade structures. These controllers are difficult to tune and if the control parameters aren't fixed properly, the performance of the converter could be degraded. The model-predictive control (MPC) is an efficient control technique especially suitable for multi-input-multi-output (MIMO) systems. Since MPC can deal with constraints and multiple control objectives very efficiently, it is an ingenious manner to adopt the concept of MPC in the control of nonlinear and discontinuous power converters.

MPC was first applied in the control of MMC as finite control set MPC (FCS-MPC) by Qin and Saeedifard (2012). Crispino et al. used MPC control strategy to regulate ac-side and circulating currents based on the predicted output voltage level, instead of the switching states possibilities. A fast MPC was proposed Gong et al. (2016) which significantly reduces the number of calculations. A control method using weighted model predictive control (WMPC)was presented by Ben-Brahim et al. (2016) which derives the applicable switching states out of the whole combinations, and applies the switching pattern with minimum cost out of the applicable switching patterns.

In this paper, a WMPC-based method is proposed for the control of MMC. This technique uses genetic algorithm (GA) to optimize the WMPC cost function by producing two optimum upper and lower arm insertion indices and then employs the submodule sorting algorithm to obtain the corresponding switching patterns. The proposed method was verified on a single-phase MMC with 10 submodules. The control program was written in MATLAB and simulations were performed using Simulink. Simulation results are presented and discussed. Results verify the practicality of the proposed technique.

The rest of this paper is structured as follows. In Section 2, topology and operation of a single-phase MMC with 10 SMs is described and the state space model of the proposed converter is derived. In Section 3, GA is brieflyreviewed. The Proposed control algorithm is described in Section 4. Simulation results are presented and discussed in Section 5. Finally, the conclusions are presented in Section 6.

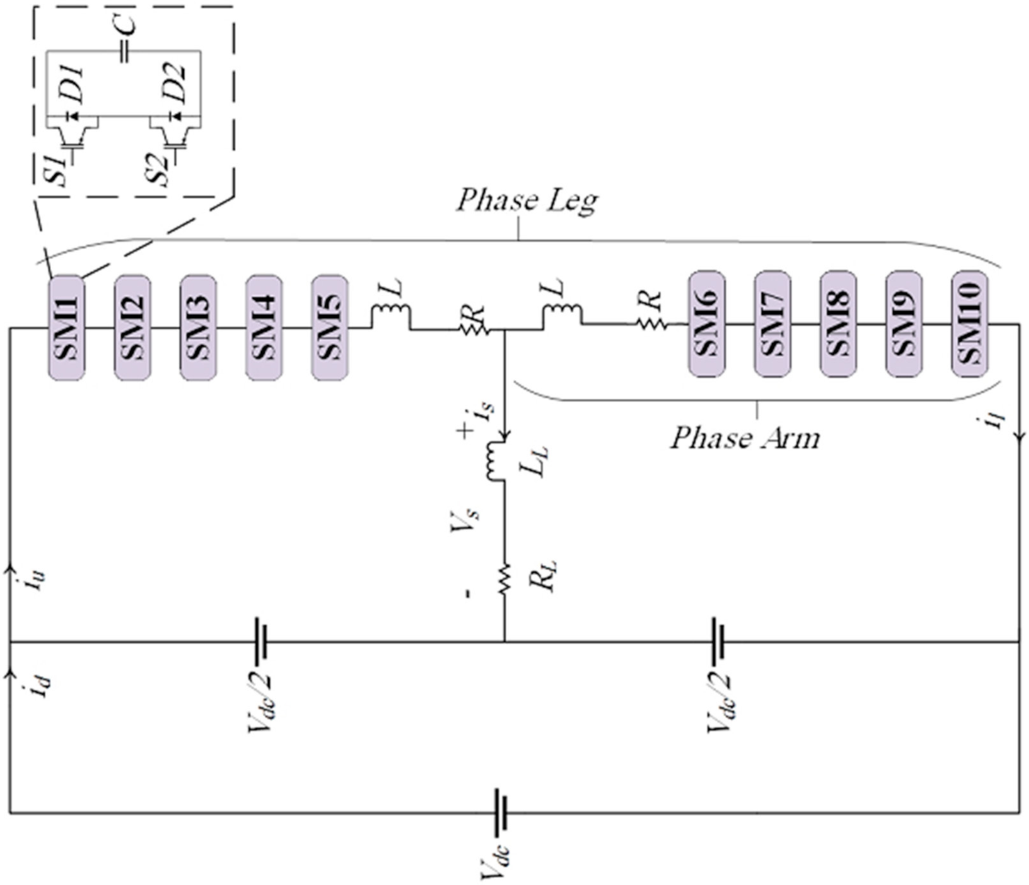

Fig. 1. Topology of a single-phase MMC with 10 SMs

2. Modelling and Analysis of the Proposed MMC

2.1. Basics of Operation

A schematic of a single-phase MMC with 10 SM feeding a RL load is shown in Fig. 1. The MMC is fed by a dc source with a constant dc voltage V_{dc}. There are two arms in the phase leg of the converter i.e., the upper arm which is denoted by subscript *"u"* and the lower arm which is dented by subscript *"l"*. Each arm comprises of 5 series-connected identical half-bridge SMs, and a series-connected inductor *L.* The resistor R represents the ohmic losses within the inductor *L*. the arm inductor suppresses high-frequency components in the arm currents, i.e., i_u and i_l. Each SM has two states:

- Inserted: when the switch S_1 is on, and
- Bypassed: when the switch S_2 is on.

When a SM is inserted, the capacitor starts to charge or discharge, depending on the arm current direction. When a SM is bypassed, however, the capacitor voltage remains constant. By inserting a number of SMs and bypassing the others in each arm, a multilevel waveform can be produced in the output terminals of the converter.

2.2. Mathematical Modelling

In the MMC shown in Fig. 1., the upper and lower arm currents i.e., i_u and i_l are expressed as

$$i_u = \frac{i_s}{2} + i_c \text{ and } i_l = -\frac{i_s}{2} + i_c \tag{1}$$

where i_s and i_c are the output and circulating currents, respectively. Therefore, the circulating current can be expressed by

$$i_c = \frac{i_u + i_l}{2} \tag{2}$$

Circulating current does not flow into the load but it increases the internal power losses and the amplitude of the capacitor voltage ripples. Sharifabadi et al. (2016) expressed the equations governing the dynamics of the upper and lower sum capacitor voltages as

$$\frac{C}{N}\frac{dv_{c,u}^{\Sigma}}{dt} = n_u\left(\frac{i_s}{2} + i_c\right) \tag{3}$$

$$\frac{C}{N}\frac{dv_{c,l}^{\Sigma}}{dt} = n_l\left(-\frac{i_s}{2} + i_c\right) \tag{4}$$

where C is the SM capacitance, n_u and n_l are upper and lower arm insertion indices, and $v_{c,u}^{\Sigma}$, and $v_{c,l}^{\Sigma}$ are the upper and lower arm sum capacitor voltages, respectively. The equations governing the dynamics of the output and circulating currents are expressed by (5) and (6), respectively.

$$\left(L_L + \frac{L}{2}\right)\frac{di_s}{dt} = \frac{-n_u v_{c,u}^{\Sigma} + n_l v_{c,l}^{\Sigma}}{2} - \left(\frac{R}{2} + R_L\right)i_s \tag{5}$$

$$L\frac{di_c}{dt} = \frac{V_d}{2} - \frac{n_u v_{c,u}^{\Sigma} + n_l v_{c,l}^{\Sigma}}{2} - Ri_c \tag{6}$$

Where R_L and L_L are the load resistance and inductance, respectively. By using the equations (3)- (6), the mathematical model of the converter can be constructed as

$$\begin{pmatrix} \frac{di_s}{dt} \\ \frac{di_c}{dt} \\ \frac{dv_{c,u}^{\Sigma}}{dt} \\ \frac{dv_{c,l}^{\Sigma}}{dt} \end{pmatrix} = \begin{pmatrix} -\frac{R+2R_L}{L+2L_L} & 0 & \frac{-n_u}{L+2L_L} & \frac{n_l}{L+2L_L} \\ 0 & -\frac{R}{L} & \frac{-n_u}{2L} & \frac{-n_l}{2L} \\ \frac{n_u \times N}{2C} & \frac{n_u \times N}{C} & 0 & 0 \\ -\frac{n_l \times N}{2C} & \frac{n_l \times N}{C} & 0 & 0 \end{pmatrix} \begin{pmatrix} i_s \\ i_c \\ v_{c,u}^{\Sigma} \\ v_{c,l}^{\Sigma} \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{V_d}{2L} \\ 0 \\ 0 \end{pmatrix} \tag{7}$$

3. A Brief Review on Genetic Algorithm

A genetic algorithm is a powerful optimization tool which, in contrast with the classic optimization algorithms, does not depend on derivation. GA uses the Darwinian theory of evolution and natural selection in order to find the best set of solutions to an optimization problem. In general, GA starts by coding the optimization variables (genes) into binary or float-point strings of length N_{var} (chromosomes). then GA starts to apply biological functions such as crossover and mutation on the population until the termination criterion is met. After termination, the best possible set of solutions is provided. In this paper, real-coded GA is employed for optimization. The float-point strings consist of two upper and lower insertion indices which are optimized throughout the algorithm.

4. Proposed Control Technique

It is noteworthy to mention that the main purpose of the MMC controller is to best track the load current while balancing the sum capacitor voltages and minimizing the ac components of the circulating current. Since the state variables are highly interrelated, if the controller smoothly controls one of the variables, it might cause degradation in the others. Therefore, one must be careful in the selection of the controller type and its parameters.

In this paper, weighted model predictive control (WMPC) is employed along with GA to control the output current of the MMC while balancing the upper and lower sum capacitor voltages and suppressing the ac components of the circulating current. Since the model is nonlinear, using conventional MPC algorithms may end in undesirable results. Therefore, in this paper, GA is employed along WMPC in order to improve the WMPC algorithm. During each sampling instant, GA uses the WMPC to derive the optimum upper and lower insertion indices. The insertion indices are then employed by the submodule sorting algorithm proposed by Lesnicar and Marquardt (2003) to obtain the corresponding switching patterns. the control algorithm, which is depicted in Fig. 2., can be explained by the following steps:

1. Measure the current state **X(k)**.
2. Predict the next state **X(k+1)** using (8) and optimize the cost function f_{cost} using GA to obtain the optimum insertion indices

$$X(k+1) = \dot{X}(k+1)T_s + X(k) \tag{8}$$

$$f_{\text{cost}} = \mu_1 \left(i_{sref} - i_s\right)^2 + \mu_2 \left(i_{cref} - i_c\right)^2 \tag{9}$$

3. Obtain the corresponding switching pattern by using the submodule sorting algorithm.
4. Apply the obtained switching patterns to the MMC.

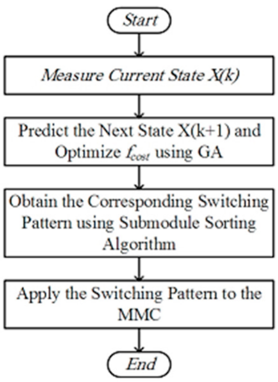

Fig. 2. The proposed control algorithm

5. Simulation Results

Simulations are carried out using MATLAB/Simulink. The control algorithm is implemented using MALTAB and it is linked to a Simulink model of the MMC shown in Fig. 1. The arm inductor and the SM capacitance are chosen in a manner that an amount of balance between the upper and lower arm sum capacitor voltages is achieved without circulating current control. The GA parameters are selected in a way that the algorithm maintains its accuracy as well as speed. GA parameters are listed in Table 1. The converter and control parameters used in simulation are listed in Table 2. It is necessary to mention that the objective of the controller is to best track the load current reference, while maintaining the circulating current at a constant dc voltage equal to the input dc current $i_d = P/V_{dc}$. The load current reference is considered to be a sinusoid with constant amplitude and frequency.

Table 1. GA Parameters

Parameter	Value
Population Size	90
Number of Genes	2
Crossover Rate	90%
Mutation Rate	10%
Maximum Number of Iterations	100

Table 2. Simulation Parameters

Parameter	Value
Input DC Voltage V_{dc}	500 v
Arm Inductance L	3.8mH
Arm Resistance R	0Ω
Load Resistance R_L	19Ω
Load InductanceL_L	50mH
Number of Submodule in Each Arm N	5
Submodule Capacitance	800μF
Load Current Reference (peak)	10A
Circulating Current Reference	1.9A
Sum Capacitor Voltage Reference	500 v
Output Frequency	50 Hz
Sampling Frequency	10kHz

5.1. Tuning of the Weighting Factors

Since the control technique used in this paper is based on weighted model predictive control, the tuning of the weighting factors is crucial for the stable operation of the MMC.As proposed by Gong et al. (2017), normally, the control of the output current is the primary objective while the control of the circulating current is the second. Therefore, $\mu_1$is chosen as the primary factor and $\mu_2$is chosenas the secondary factor. These factors are determined experimentally based on the results obtained by simulation. Simulations areperformed for different values of $\mu_2$while $\mu_1$is fixed at 1. The factors which caused stable and desirable results were chosen. For the case study presented in this paper, the weighting factors are equal toμ_1=1 and μ_2=0.3.

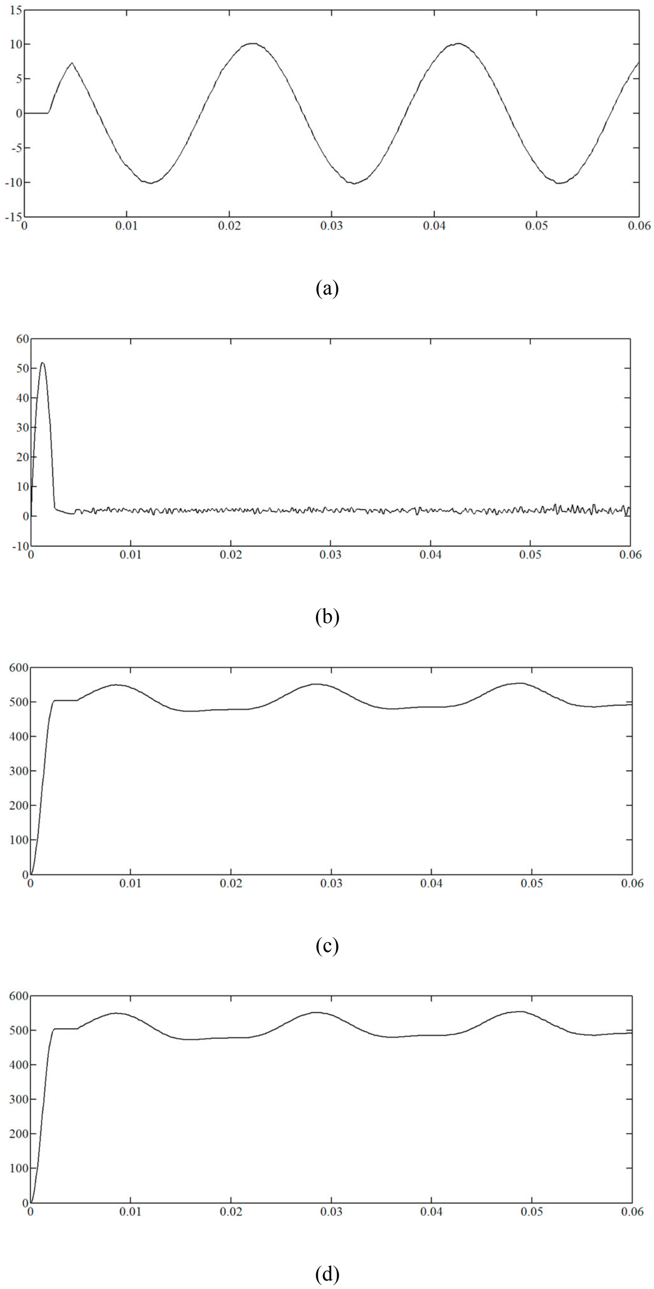

Fig. 3. Simulation results for the tuned weighting factors: (a) output current; (b) circulating current; (c) upper arm sum capacitor voltages; (d) lower arm sum capacitor voltages

5.2. Simulation Results for the Tuned Weighting Factors (μ_1 =1,μ_2=0.3)

The corresponding results are plotted in Fig. 3 (a)-(d). The controller has successfully tracked the load current reference with a low THD. The circulating current is oscillating within a negligible band around its reference value. The sum capacitor voltages are oscillating around 500*v* with low ripple percentage. Simulation results demonstrate that employing GA along with WMPC has returned excellent results.

6. Conclusion

A new method for MMC control is proposed in this paper. The proposed method is based on WMPC and uses GA as its optimizer. At each sampling instant, GA optimizes the WMPC cost function by producing two optimum insertion indices. The insertion indices are then transformed into switching patterns using the submodule sorting algorithm. The proposed method was tested on a single-phase MMC with 10 submodules. the weighting factors in WMPC were selected based on simulation results. Simulation results were provided and discussed. The results prove the practicality of the proposed algorithm.

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