High-voltage pulse generator using sequentially charged full-bridge modular multilevel converter Sub-modules, for water treatment applications

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Abstract: This paper proposes a new high-voltage pulse generator (PG) fed from a low-voltage DC supply \(V_s\), which charges one arm of \(N\) series-connected full-bridge (FB) modular multilevel converter (MMC) sub-module (SM) capacitors sequentially, through a resistive-inductive branch. By utilising FB-SMs, the proposed PG is able to generate bipolar rectangular pulses of peak \(NV_s\) and unipolar rectangular pulses of either polarity, at high repetition rates. Asymmetrical pulses are also possible. The proposed topology is assessed via simulation and scaled-down experimentation, which establish the viability of the topology for water treatment applications.

1 Introduction

Applying lethal electroporation is required for the disinfection process in water treatment applications. Harmful microorganisms are subjected to an electric field \(E\) such that \(E > E_{cr}\) where \(E_{cr}\) is the critical electric field beyond which the cell-membrane cannot reseal its pores [1]. The created pores lead to biological cell death, and disinfection results. In order to create such an electric field across the treatment chamber, a high-voltage (HV) for sufficient time should be applied. Recent research confirms the effectiveness of applying HV-pulses of a few kV with a duration of microseconds [2]. Hence, both energy efficiency and the lethal electroporation criteria are met. Thus, a low-power long duration input is used to provide high-power short-duration pulses for the electroporation as illustrated in Fig. 1 [3]. Thus, a controllable, high efficiency power electronics-based converter can be utilised.

Utilising modular multilevel converter (MMC) sub-modules (SMs) in the power conversion stage is viable. Both full-bridge (FB) and half-bridge (HB) SMs, illustrated in Fig. 2, can be employed in pulsed power applications [4–13].

Since SMs have capacitors, these can facilitate flexible pulse waveforms generation and flexible individual SM control [8, 9].

This paper exploits individual FB-SM control to charge capacitors sequentially as proposed in [13]. Efficient SM-capacitor charging is achieved through an \(rL\) branch, which allows fast individual SM-capacitor charging. The proposed topology utilised one arm of series-connected FB-SMs with the ability of generating bipolar and unipolar rectangular HV pulses. The generated pulses can be tailored to meet the application requirement by controlling the pulse polarity magnitude and/or the pulse duration.

This paper is structured as follows: next the proposed converter is introduced in Section 2, highlighting its operational principle. Simulation and experimental results are presented in Sections 3 and 4, respectively. Conclusions are drawn in Section 5.

2 Proposed pulse generator topology

The proposed PG topology is shown in Fig. 3. The PG is formed of \(N\) series-connected FB-MMC SMs, which are charged sequentially from a low-voltage DC (LVDC) supply \(V_s\) through an \(rL\) branch via the reverse blocking switch \(S\). As illustrated in Fig. 2, the individual FB-SM is formed of four insulated gate bipolar transistors (IGBTs) connected with a capacitor. The FB-SM terminals, A and B, are short-circuited (bypassed \(V_{AB} = 0\)) in two

![Fig. 1 Pulsed power energy concept](image-url)
cases when \((T_1 \text{ and } T_3)\) or \((T_2 \text{ and } T_4)\) are switched ON with the other two switches OFF. A positive capacitor voltage is applied, \(V_{AB} = +V_{SM}\), across terminals A and B when \((T_1 \text{ and } T_2)\) are ON and \((T_3 \text{ and } T_4)\) are OFF. When \((T_1 \text{ and } T_2)\) are OFF and \((T_3 \text{ and } T_4)\) are ON, a reverse polarity capacitor voltage appears across terminals A and B, \(V_{AB} = -V_{SM}\). Thus, with appropriate control of individual SM zero voltage, positive and negative voltages can be applied across the load. The topology incorporates two additional switches, switch \(S\) and switch \(Q\). Switch \(S\) provides a closed current path during sequential charging the SM capacitors, while switch \(Q\) provides a closed current path for SM capacitors to discharge across the load, \(R\), and forming the required pulse waveform. When \(S\) is ON, \(Q\) is OFF and vice versa. The switch \(S\) must have a high reverse blocking capability, formed of series-connected IGBTs and diodes [14–19]. The IGBTs are rated at \((N + 1)V_c\) and the diodes are rated at \((N - 1)V_c\). This series connected \(S\) and \(D_1\) only support a high voltage, and switch current at low-voltage \(V_c\). Switch \(Q\) is rated at the LVDC supply \(V_s\) and is formed of an IGBT \(Q\) with anti-parallel diode \(D_2\) to allow bidirectional current flow.

Fig. 4 shows a typical rectangular pulse waveform generated by the proposed PG. The circuit during each stage of generating bipolar rectangular pulses is illustrated in Fig. 5. Fig. 5a shows the circuit during positive pulse generation (stage 1 in Fig. 4) where individual SM capacitors are inserted in series (by turning ON \(T_1\) and \(T_2\) SM switches with \(T_3\) and \(T_4\) switches OFF) and switch \(Q\) ON with its antiparallel diode reverse biased. Fig. 5b shows the charging current path for individual SM-capacitors (stages 2 and 4 in Fig. 4). The load is isolated and has zero-voltage during the SM charging process. Finally, in stage 3, a negative voltage can be formed across the load, with SM switches \(T_1\) and \(T_2\) OFF and \(T_3\) and \(T_4\) switches ON. Switch \(Q\) is OFF and its antiparallel diode conducts, allowing a discharging current to flow.

A wide range of bipolar rectangular pulses can be generated by the proposed PG. Both symmetrical and asymmetrical pulses can be generated. The zero-time load voltage period can be combined by activating stages 1 and 3 successively and delaying the charging process. Bypassing the generation of a specific pulse polarity
(stage 1 for a positive pulse and stage 3 for a negative pulse) leads to unipolar pulse generation.

3 Simulation results

The proposed PG is simulated using Matlab/Simulink, with five FB-SMs and a 2 kV input supply voltage, the complete simulation specifications are given in Table 1. The selection of SM capacitance and the input charging $r_L$ branch is similar to that in [13].

With a 2 kV supply, all SM capacitors are charged to 2 kV sequentially. Then if all the SMs are inserted simultaneously, a peak voltage of 10 kV is generated across the load. Fig. 6a shows bipolar pulses of 10 kV peak voltage with $t_p = t_n = 10 \mu s$ and a repetition time of $T_s = 120 \mu s$. The five SM capacitor voltages are shown in Fig. 6b, while the charging input current is in Fig. 6c.

Several bipolar pulse variations are simulated in Fig. 7. In Fig. 7a, symmetric bipolar pulses of 10 kV peak voltage with $t_p = t_n = 10 \mu s$ and a repetition time of $T_s = 70 \mu s$, with combined zero load voltage durations, are presented. Asymmetric bipolar pulses are shown in Figs. 7b and c. In Fig. 7b, both pulse polarity voltages are 10 kV, while the pulse durations are $t_p = 10 \mu s$ and $t_n = 20 \mu s$. Fig. 7c shows asymmetry voltage magnitudes, where the positive peak voltage is 6 kV and the negative voltage peak is 10 kV, with $t_p = t_n = 10 \mu s$.

Asymmetric bipolar pulses of 20 \mu s positive-pulse duration and 4 kV peak and 10 \mu s negative-pulse duration with 8 kV peak, are shown in Fig. 7d.

Finally, unipolar pulses of 10 \mu s pulse duration with 10 kV peak positive polarity, and 6 kV negative polarity are shown in Figs. 8a and b, respectively.

4 Experimental results

Scaled-down experimentation with three SMs is used to assess the proposed PG with the specifications in Table 1. Fig. 9a shows generated symmetrical bipolar pulses with a peak voltage of 300 V, pulse duration of 20, and 400 μs repetition time. Fig. 9b shows the three SM capacitor voltages, which fluctuate around 100 V, the input voltage. The input charging current is shown in Fig. 9c. Combined zero-load voltage duration pulses with asymmetric pulse voltage and pulse duration is shown in Fig. 10a, with a positive peak voltage of 100 V and duration of 20 μs, while the negative peak is 300 V with duration of 10 μs. Finally, unipolar pulses with a negative polarity of 300 V peak and 20 μs duration are shown in Fig. 10b.

5 Conclusion

This paper presented a new PG topology to generate HV pulses, hence, can be used in lethal electroporation applications such as water treatment. The PG is based on FB-MMC SMs, which provide modularity and scalability of the topology. Individual SM capacitors are charged sequentially through a reverse blocking semiconductor switch and an $r_L$ branch from an LVDC input supply. A bidirectional switch is required, such that both positive and negative pulse polarities can be generated across the load. The generated pulses are flexible, whereas appropriate insertion/bypass of the SM-capacitors allows symmetrical and asymmetrical bipolar pulse generation as well as unipolar pulse generation across the load. The proposed topology was assessed via simulation and scaled-down experimentation, which established the viability of the topology for lethal electroporation applications.

6 Acknowledgments

This work was supported by the Qatar National Research Fund (a member of the Qatar Foundation) under NPRP Grant (7-203-2-097). The statements made herein are solely the responsibility of the authors.
Fig. 5  Circuit configuration during the generation of a bipolar pulse cycle
(a) Stage 1, (b) Stages 2 and 4, (c) Stage 3

Table 1  Simulation and experimental specifications

| Parameter            | Simulation | Experimental |
|----------------------|------------|--------------|
| LVDC input voltage   | $V_s$      | 2 kV         | 100 V        |
| input inductance     | $r_L$      | 0.1 Ω and 2 μH | 0.5 Ω and 5 μH |
| number of SMs/arm    | $N$        | 5            | 3            |
| load resistance      | $R$        | 1 kΩ         | 1 kΩ         |
| SM capacitance       | $C_{SM}$   | 5 μF         | 15 μF        |
**Fig. 6** Generation of 10 kV symmetrical bipolar pulses

(a) Voltage pulses across the load, (b) SM capacitor voltages, (c) Input charging current of SM capacitors
Fig. 7  
Bipolar HV pulses
(a) Combined zero-load voltage duration, (b) Asymmetrical pulse durations, (c) Asymmetrical pulse magnitudes, (d) Asymmetrical pulse durations and magnitudes

Fig. 8  
Unipolar HV pulses
(a) Positive polarity, (b) Negative polarity
7 References

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Fig. 9 Scaled-down experimental results
(a) Symmetrical bipolar pulses, (b) The three FB-SM capacitor voltages, (c) Input charging current

Fig. 10 Scaled-down experimental results
(a) Asymmetrical bipolar pulses with combined zero-load voltage durations, (b) Negative polarity unipolar pulses
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