A Marx-Based Power Converter Topology as a Current Source for Pulsed Magnets in Particle Accelerators

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***Abstract*— A modified Marx-based solid-state topology for supplying inductive loads is presented. The basic principle of charging capacitors in parallel and discharging them in series is conserved. Due to the negative *di/dt* phase the inductive load imposes a reversible voltage power converter. Furthermore, in some applications such as eddy current septum magnets a negative current is required as well. The presented topology allows the production of controlled half or full sine waves, with or without short or long flat-tops. The solution is able to regenerate back to the capacitor banks the energy from the magnet. To shape the desired current it is possible to time-shift the discharge of different Marx cells. Numerical simulations are used to illustrate the functionalities of this solution. This flexible converter can be easily used for all pulsed current converters in accelerator facilities with a high degree of modularity and flexibility.**

Keywords*— Accelerator magnets; Converters; Modular construction; Pulsed power supplies.

I. INTRODUCTION

In particle accelerators pulsed magnets are typically used in Linacs, transfer lines, as well as in injection and extraction areas of synchrotrons accelerators. The required power converter current and voltage ranges can be very wide and depend on the beam energy [1], and the actual magnet and components integration inside the buildings [2]. This is even truer for large physics research facilities such as CERN, where several accelerators at different energies needs a multitude of magnets differently rated. In particles beam multi-turn injection and ejection areas are typically equipped with a set of magnets composed of 3 or 4 slow bumper magnets (BSW) coupled with one septum magnet as illustrated in Fig. 1. A kicker magnet (fast) is used for single-turn beam injection or ejection only, where in less than one turn of the beam around the synchrotron the kickers “kicks” the whole beam into the septum [3].

This paper presents a modular topology based on the solid state Marx generator. This topology is typically used in high voltage applications; however, it is demonstrated that a modified version of it can be used as a modular high pulsed current supply for magnets. It is of great importance that the powering solutions for such big facilities is standard and modular in order to reduce the initial cost, the maintenance efforts and cost, and the spare parts number.

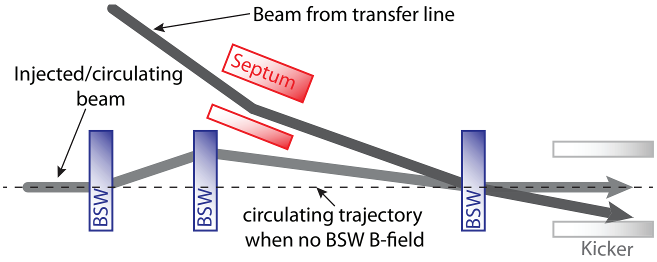

Fig. 1. Basic injection bumper and septum magnet configuration (ejection configuraiton is similar with beam direction inverted).

II. TYPICAL POWER CONVERTERS REQUIREMENT

A. *Typical current and voltage specifications*

Depending on the accelerator configuration and operation the multi-turn beam injection process can last between tens to hundreds of microseconds. During this time period the magnetic field has to be stabilised and within a defined specification. As the beam passes through the septum magnet during this period only (true for injection and ejection), its magnetic field and current specifications are mainly defined during this short period of time (10µs-100µs range). Fig. 2 illustrates the concept of magnetic field or current specification with two current, or magnetic field, shapes examples. A certain magnetic flux stabilisation time, due to eddy current decay, is required between the beginning of the flat-top and the actual particles beam passage into the magnet.

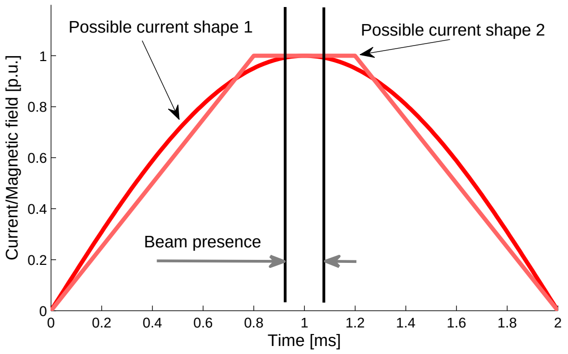

Fig. 2. Examples of current shapes in a septum magnet.

Due to the inductive load the voltage provided by the power converter shall be positive when $di/dt>0$ and negative during the $di/dt<0$ phase. As septa magnets shall be operated in a relatively fast pulsed mode (ms range), and due to voltage insulation limitations, their equivalent inductance shall remain small. Typically one can find values in the range of 10µH. These small inductive values coupled with a typical reduced space for their installation impose typical nominal peak currents in the range of a few tens of kA. This makes the power converter design challenging for two main reasons:

1. Low inductance → Low voltage ripple is required to reduce current ripple;
2. High current → A matching pulse transformer is often required to adapt the magnet current level to the power converter one, usually made of components rated in the kA range;

The aim of a set of bumper magnets is to create a closed orbit particles beam bump during an injection or an ejection process such that the tangential angle (w.r.t. the normal circulating orbit/trajectory) is similar between the injected/ejected beam and the circulating one.

The typical current shape is sinusoidal. Fig. 3 illustrates the time ranges where the particle beam circulates in the magnets for the injection and the ejection cases. In contrast with a septum magnet the beam circulates when the magnet current is varying. Furthermore, to ensure a precise closed orbit of the beam bump, it is necessary to guarantee a precise synchronous operations of all bumper magnets. The relative current precision between bumper magnets during beam presence becomes an essential issue to be addressed.

The sinusoidal current shape can be considered as a legacy where a simple capacitor discharge was the only mean to comply with the specifications in the past. The need for more relative precision during ramp-ups and ramp-downs for more efficient ejection and injections imposes new solutions where, even for bumper magnets, power converters can be controlled during the whole period.

Constructively bumper magnets can present higher inductances when compared to their coupled septum. Typical currents are in the range of the kA and inductances between tens and hundreds of µH.

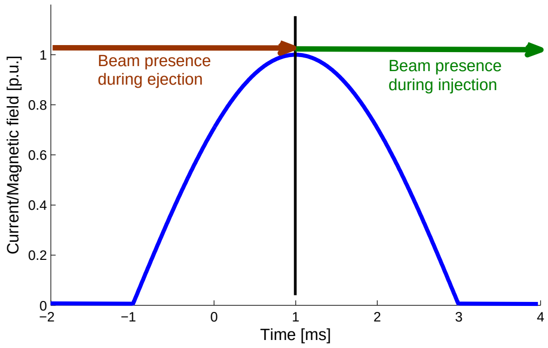

Fig. 3. Examples of current shape in a bumper magnet and identification of the beam presence for which relative precision between bumpers is required.

B. Examples of existing power converter solutions

At CERN most of bumper and septum magnets power converters are ageing, and are based on the resonant principle between a simple capacitor bank and the inductive magnet. Notice that with such a solution the current regulation is defined by the initial capacitor voltage before the discharge (typically ensured by a thyristor). During the discharge phase no control is possible.

For septum magnet a more sophisticated topology, always based on a capacitive discharge, includes the addition of a 3rd harmonic and an active filter to obtain a regulated current flat-top (cf. Fig. 2). This concept [4] is illustrated in Fig. 4, and typical (arbitrary though) current curves are presented in Fig. 5. The advantage is a closed-loop operation during the flat-top period, allowing high precision regulation, with linearly operated MOSFETs (several in parallel) avoiding any switching harmonics injection into the septum.

More recently a novel multi-stage, IGBT-based, topology has been proposed and implemented at CERN for septum magnets [5]. This solution uses modern power electronics components combined with digital regulation and monitoring, allowing higher current precision.

C. The need for a modular solution

The existing topologies presented in Section II.B all present very interesting features. From the simplicity and robustness of capacitive discharge-based topologies to high precision controlled modern power converters. However, for a large scale consolidation plans (such as the current one at CERN), a more generalized and modular approach could be beneficial.

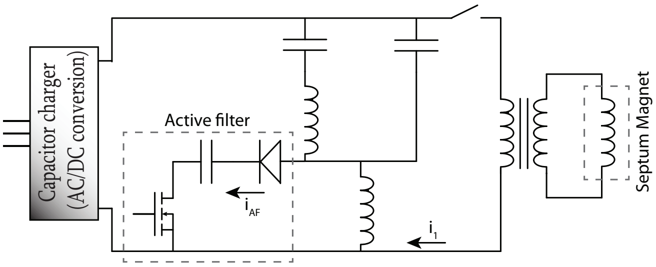

Fig. 4. 3rd harmonic injection + active filter concept [4].

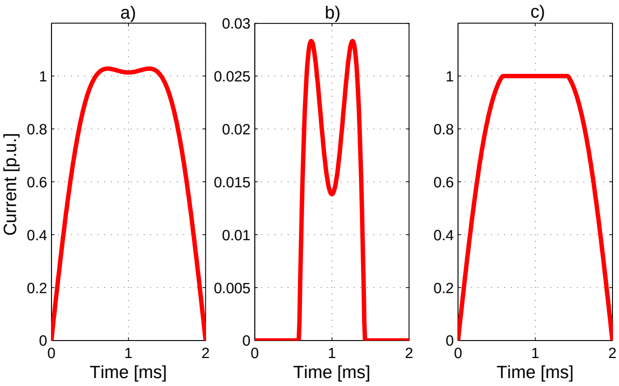

Fig. 5. Current shapes in 3rd harmonic + active filter concept – a) I_1 current if active filter not acting, b) current in the active filter when acting, c) current I_1 (equivalent to septum current), when active filter acting.

Indeed the specifications in terms of current and voltages for all the injection/ejection bumper and septum power converters to be replaced at CERN span from 1kA to 4kA and from 2kV to 6kV. In combination with several basic resonant periods and flat-top length requirements, it becomes essential to chase a modular design to avoid the optimization of tens of different converters versions.

A combination of simple capacitor discharge with an active filter (existing solution) and a multistage modular concept (modern solution) is the idea behind the proposed solution.

III. NOVEL MARX TOPOLOGY-BASED CONVERTER

A. *The Basic topology*

The Marx topology is very well known in the high voltage domain. Developments in the last two decades showed new solid-state topologies for klystron modulators [6] with variants going to generalised topologies for positive and negative output voltages [7]. However the developed solutions cannot directly be applied to inductive loads with minimised switches number.

The principle schematics combining the advantages of previous CERN solutions with the Marx-based topology principle is depicted in Fig. 6. For simplicity the pulse transformer is omitted from this principle analysis. The Marx basic principle is conserved where capacitors are charged in parallel (Fig. 6 a)) and discharged in series (Fig. 6 b)). An active filter is placed similarly to the existing topology illustrated in Fig. 4. During the discharging phase the voltages across each capacitor reverses as the magnet's $di/dt<0$, imposing the necessity to have all switches bidirectional in voltage and unidirectional in current. A transistor + serial diode or a thyristor switch is therefore necessary (Fig. 7). The main advantage in using transistors (e.g. IGBTs) lies in the possibility of using the Switches S_b as a distributed serial crowbar in case of a magnet fault (e.g. to ground) or a capacitor fault in the power converter.

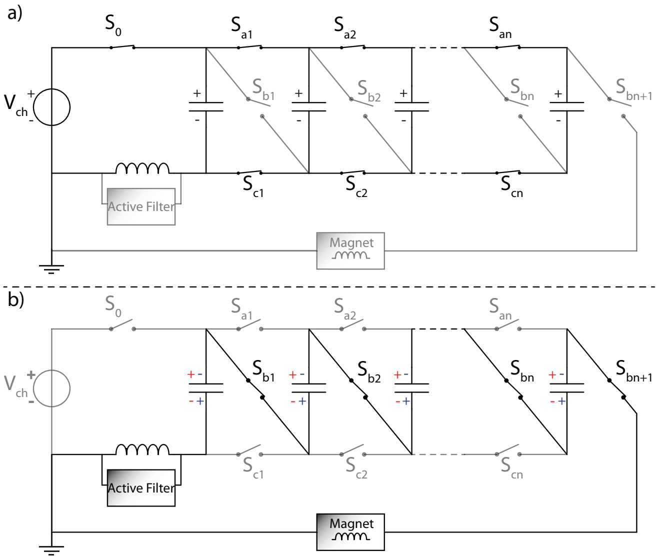

Fig. 6. Marx topology principle applied to inductive loads – a) charging phase, b) discharging/pulse forming phase.

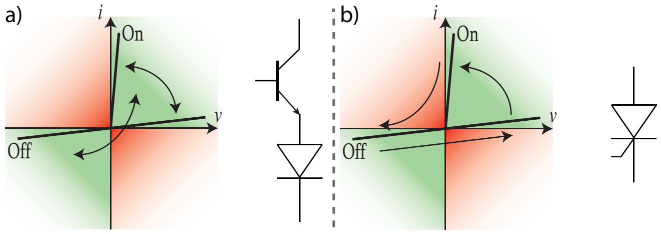

Fig. 7. Possible 3-segment switches – a) with turn on and turn off capabilities (transistor + serial diode), b) with turn on capability only (thyristor).

B. *Energy recovery from the magnet*

At the end of each cycle the energy from the magnet is recovered and the voltage across each capacitor bank is reversed. One way to handle this situation is to destroy all the capacitor energy via resistors. This is clearly not an elegant solution and shall be avoided.

A solution allowing the capacitors voltages reversal after energy regeneration from the magnet is illustrated in Fig. 8. This is achieved by the voltage reversal system which creates a resonant circuit between all capacitor banks C_i (i being the index expressing the module number) and the active filter and reversal inductances L_{af} and L_{rev} respectively. The reversal inductance L_{rev} value can be selected such as the resonant frequency f_{rev} (1) is low enough to mitigate losses and increase components lifetime. Furthermore this circuit allows to prematurely stop the voltage reversal process by opening the switch S_{rev}. This is important in cases where the subsequent cycle needs a lower initial capacitor voltage (and thus magnet current). In this case, the opening action of S_{rev} turns on the diode D_{des} which allows to destroy (through resistor R_{des}) the excess energy (R_{des} design is related to L_{rev} choice). In the opposite case, when the next cycle requires more initial voltage across the capacitor banks C_i, S_0 is turned on (also 3 segment switch required) to use the capacitor charger represented by V_{ch}.

$$f_{rev} = \frac{1}{2\pi\sqrt{(L_{af}+L_{rev})\sum_{i=1}^{n} C_n}} \tag{1}$$

C. *Application to bumper and septum magnets*

For bumper magnets, where a simple sine wave discharge is typically required (Fig. 3), all switches S_{bi} (Fig. 6 b)) are turned on at the same time. In this configuration the active filter, which is rated at a fraction of the output voltage and current, can act during the full discharge period. This means that the relative precision amongst all bumper magnets ensuring a closed bump can be controlled.

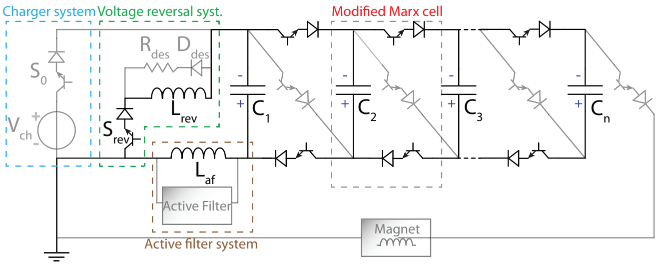

Fig. 8. Resonant principle to reverse the capacitors voltages after energy regeneration from magnet. Illustration of the basic topology.

In septum magnets applications a regulated flat-top is needed. There are three different control methods among others that can be adopted, all with an impact on the power converter dimensioning:

1. Synchronous discharge of all Marx cells: In this case the active filter shall be dimensioned such that the current sine wave tip is compensated during the flat-top time. The longer the flat-top duration, the higher the dimensioning current of the active filter. Alternatively the base resonant frequency between the series connection of the capacitor banks C_i can be decreased, at the expenses of an over-dimensioning of the power converter (except the active filter), of the magnet (increased losses), and of the pulse transformer (higher flux swing/magnetic material necessary).
2. Delayed discharge of Marx cells: To better shape the current pulse irrespectively to the active filter it is possible to discharge the Marx cells in a specific sequence, as performed with solid-state Marx klystron modulators for long pulses. When the load is inductive the analysis is more complicated as the insertion of capacitors during the pulse modifies the discharge resonance frequency. A predictive control of the time instant of insertion of supplementary capacitor bank becomes tedious (especially for electronics implementation). This is not the core subject of this paper; however Section IV illustrates the concept by numerical simulation results. On top of that, after the current pulse ends, regenerated magnet energy won't be equally distributed over Marx cells, therefore, causing unequal voltages over capacitors C_i. Inrush current, due to unequal capacitor bank voltages during charging period, can be solved by adding small inductances in series with capacitors C_i.
3. Discharge of Marx cells with freewheeling period: Considering short time period in which the beam is present, magnet current can be allowed to run in freewheeling during the flat-top. In this case, the active filter must compensate for the magnet current decrease due to voltage drop over resistances and switches in the freewheeling path. Generally, this approach consists of three parts: capacitor discharge (current increase), freewheeling (current flat-top) and capacitor reverse charge (current decrease). The longer the flat-top duration, the higher the dimensioning current of the active filter due to larger current drop that have to be compensated.

D. Extension to a voltage and current reversible Marx-based topology – Final basic topology

In eddy current septum magnets a full sine wave current can be supplied in order to accelerate the long magnetic field leakage decay time [8]. An extension of the presented Marx-based topology for this application is illustrated in Fig. 9. Switches S'_{bi} allow inverting the current flow direction. To guarantee a smooth transition from positive to negative current flow direction the gates of switches S'_{bi} can be triggered before the actual current zero crossing (allowing a current commutation from S_{bi} to S'_{bi}). In Fig. 9 the topology has been simplified by changing the ground position. In this final basic topology the functions of L_{af} and L_{rev} are decoupled (in (1) L_{af} is then omitted), S_0 of Fig. 8 is not necessary anymore (function of switches S_{ai} and S_{ci}), and all Marx cells are identical. The capacitor charger needs isolated outputs though.

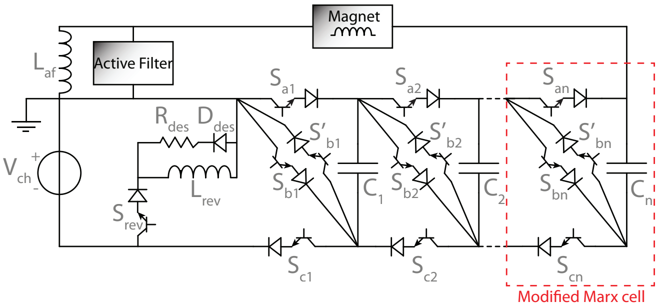

Fig. 9. Final Marx-based topology for full wave current into inductive loads.

E. Modular and easy mechanical integration for efficient operations

The driving factor for proposing such a solution lies in a simple modular topology able to comply with several magnet specifications. For each one of them a different capacitor bank value is required to obtain the specified current shape (resonance period). The number of modules can also widely vary depending on the peak voltage level and/or on the flat-top length in case a delay discharge sequence is used. A simple mechanical integration of each module is essential to guarantee this flexibility and to obtain a high accelerator availability (fast module changing during operational interventions).

As every switch of a Marx cells is operated, i.e. turn-on and turn-off cycle, once per beam injection or extraction only (for CERN's PS complex at a repetition rate of 1.11Hz), the average switching losses are negligible. In this case fast switch turn-on or turn-off is not required, therefore simplifying integration of the different components into racks (and mitigating EMC issues). For instance all the capacitor bank C_i do not have to be close to the switching components, making possible to have dedicated and modular capacitor racks. Thanks to this modular topology oil immersed high voltage capacitors can also be avoided, simplifying safety related integration components (e.g. retention backs).

IV. EVALUATION BY NUMERICAL SIMULATIONS

A simple numerical simulation has been performed for concept validation purposes. In Table 1, main parameters of the simulated Marx-based topology are listed.

TABLE I. PARAMETERS OF SIMULATED MARX-BASED TOPOLOGY

Parameter	Symbol	Value
No. of Marx cells		8
C_i	µF	850
Input (charging) voltage	V	500
Output voltage, maximum	kV	4
Output current, maximum	kA	4
Minimum flat-top period	µs	100

A. Simple sinusoidal discharge

In Fig. 10, a simple sinusoidal discharge is simulated using all eight Marx cells. All cells are synchronously switched/discharged through a magnet load, thus providing half-sine waveform current pulse. On the right hand side of Fig. 10, the required active filter current in case a flat-top is needed is depicted for two cases: 2 quadrant or 4 quadrant active filter operation. A 4 quadrant active filter is more complex; however, lower nominal current is required. The required active filter bandwidth is defined by the resonant frequency of the pulse.

B. Sequential capacitor discharge

In Fig. 11, the more complex approach of sequential capacitor discharge is shown. For the sake of simplicity, only three Marx cells were involved in the discharging/pulse process. Required active filter current has lower amplitude in comparison to sinusoidal discharge, however the compulsory bandwidth is much higher. Very high active filter bandwidth requirement coupled with complex control, makes this approach unfavourable.

C. Discharge with freewheeling period

In Fig. 12, magnet current waveform using capacitor discharge with freewheeling period is depicted. This solution requires low current from the active filter to deliver the flat-top. Moreover, the bandwidth of the filter is very low. Preferably, the active filter can be implemented using linear regulation, thus omitting any switching harmonics during the flat-top.

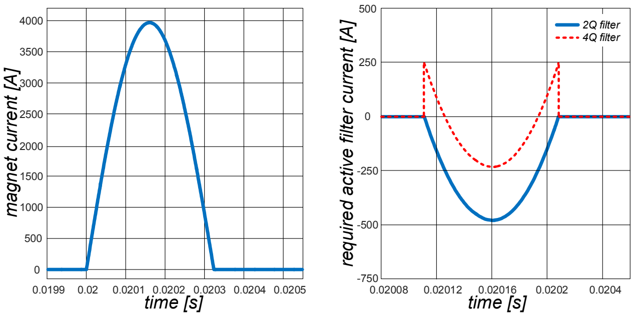

Fig. 10. Simple sinusoidal discharge and required active filter current for the flat-top production.

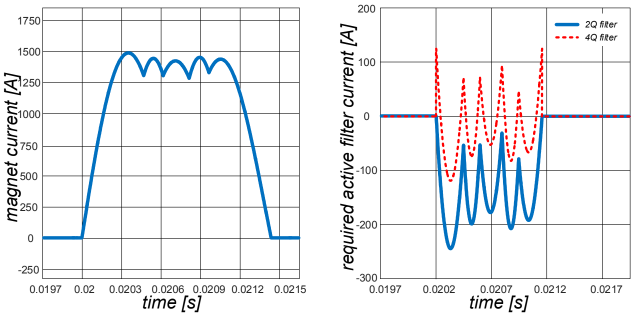

Fig. 11. Sequential capacitor discharge of three Marx cells and required active filter current for the flat-top.

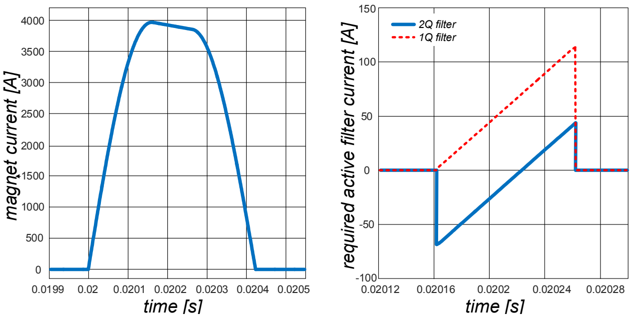

Fig. 12. Discharge with freewheeling period and required active filter current for the flat-top.

Average losses in the linear stage are limited since low pulse repetition rates are required.

V. CONCLUSION

A Marx-based topology has been modified and adapted to supply inductive loads. The proposed solution allows feeding accelerator pulsed magnets with controlled half or full sine waves, and with the possibility of presenting a short or long flat-top. Furthermore the energy fed to the magnet is regenerated into the capacitor banks. The modularity and absence of fast switching actions within the Marx cells allow a simple mechanical integration, increasing the flexibility of this topology versus a wide variety of current and voltage ranges specifications. The presented topology is very flexible and presents many operational and economic advantages, making it the suitable choice for the undergoing consolidation campaign at CERN.

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