Perspective On Plasma Technology Employing Pulsed High Voltage Topologies

1.R.Senthil Kumar and 3.Harshavardhan Naidu
1,3Department of Electrical and Electronics Engineering
1,3Vel Tech High Tech Dr.Rangarajan Dr.Sakunthala
Engineering College , India
rskumar.eee@gmail.com, sapineniharsha@gmail.com
2.K.Mohanasundaram
Department of Electrical and Electronics Engineering
KRP Institute of Engineering and Technology , India
kumohanasundaram@gmail.com

Abstract - Versatility of the plasma technology has grabbed its application in a board field starting from the field dealing with microorganism to space science, the primary requirement the technology initiates with the generation of pulsed high voltage of various range as per the application it varies from 0.1-100 KV/cm. the article bestows the evolution and classification of pulsed HV after a comprehensive review of various topologies employed for plasma technologies, it provide a comparative study of various general topologies with an insight of it merits and demerits. Spot light is being showered over the evolution opted by the topologies as the solution for the issues faced mainly back corona effect and effect on line due the harmonics pumped by the pulsed HV generators.

Keywords - pulsed HV generator, back corona, effect on line, plasma technology.

1. Introduction
In general Plasma technology are categorised as hot or cold /non thermal plasma technology, due to enormous potential its venture is growing rapidly in various industrial and commercial application the following section II brief the effective need of non-thermal plasma technology among some of its application, it also insight the effectiveness of pulsed HV for following application and the required HV/cm².

Section 3 perceive the evolution in topologies of PHVG and gives the classification of PHVG, it brief the variation opted, working, benefits and problem encounter in various topologies. Section 4 it provide the conceptual study on bipolar topologies for the fact that bipolar topologies offers a superior results compare to unipolar topologies for all the application discussed in the section 2. Along with that the solution offered by them are highly reliable and simple.it also hold comparison table displaying the merits and demerits of various bipolar topologies.

Section 5 discuss the effect on the main line due to PHVG powering the non-thermal plasma application, as per the fact that all the nonlinear components employed in generating pulsed HV distort the supply power, there by effecting all the equipment connected in the same line by pumping harmonics. It covers various topologies which are employed for powering the discharge electrode of ESP and their THD values, it also emphasise the effect of auxiliary filter along with topologies in the part of reducing the harmonics being pumped into the main line. Section 6 focus on the back corona effect which is most common at HV pollution control plasma application. It create a drastic negative impact in the effective functioning of system by reducing the collection efficiency. This phenomenon occur when plasma technology is employed to collect high resistive particle from the contamination. Though there are several solution are put forth to avoid this phenomenon based on opting changes in design and principle of operation. This article mainly insight the solution which are offered by the means various electrical topologies powering the discharge electrodes.

2. Application of plasma technologies
Electrostatic precipitator
Over several decades they play a vital role in reduction of pollutants in the atmospheric air, they not only filter out suspended dust particle alone in the flue gas, it also removal of sulphuric acid, lead oxide, ammonia etc. [1] from various industries rule the major infrastructure of a countries. knowing the serious consequence, worldwide installation of electrostatic precipitator is made mandatory in industries such as refineries, distilleries, cement, thermal power plant etc.

Water Treatment
The main objective in treating the water is to satisfy the end user with portable water, for this it becomes necessary to remove the contamination and microorganism, though there are several conventional to do this purpose mainly they are based on treating water with several chemical, which in turn results many medical side effects. Plasma based water treatment provide a solution for chemical free water treatment [2].

Electroporation
It is a field in which permeability of cell membrane are increase by applying an electric field, if the permeability is increased then it becomes easy to inject DNA, chemical, gene or drugs into it, though it has several applications its role in the field medicine in treating cancer and gene transfer is indispensable, as the offer safe, cheap and easy technique [3].

Spacecraft propulsion
Phenomenon behind the propulsion is corona wind. Electrostatic forces created by the corona discharge induce the flow of air which propels the space craft, over last six decades the researches are adopted in the field as it ensures low cost, more versatile, compact and weight less alternatives to the fuelled propellers, these unique features are fruitful for the development of micro, Nano, Pico satellites.
Food processing

Prior aim in processing the food is to preserve the food from getting spoiled, due to microorganism, hence it becomes to make the inactive, for these activities conventionally chemical treatment or thermal treatment were carried out, but in this process physical properties such as real nutritional value, colour, texture and flavour get altered [4]. In plasma treatment method microbes are inactivated without changing the physical properties.

Micro bio industries

Plasma technology is promising technique in major activities of micro bio industries such as microbial inactivation, cellular component extraction, growth stimulation etc at low cost, simple and save technique [5]. Table 1 shows the Plasma Technology Application Vs Required Kv/Cm.

Table 1: Plasma Technology Application Vs Required Kv/Cm

| No | Application                      | kV/cm |
|----|----------------------------------|-------|
| 1  | Electrostatic precipitator        | 30    |
| 2  | Water treatment                   | 10-30 |
| 3  | Electroporation                   | 0.1-100 |
| 4  | Spacecraft propulsion             | 25-40 |
| 5  | Food processing                   | 10-50 |
| 6  | Micro bio industries              | 10-100 |

3. Classification of Various Pulsed High Voltage Generators PHVG

Based on numerous publications on PHVG, broadly it can be grouped under three categories based on the methodology adopted as displayed in the Figure 1, first the conventional methods like blumlein lines, PFNs and Marx generators PHVG (MPHVG). Second it is based pulse transformer, which of several type namely closed magnetic core, air core transformer and tesla open magnetic core are commonly used [6]. Third is due the several evolutions in the power electronic converters leads to other three topologies such as modulated converter based PHVG (MMCPHVG), non-modulated converter based PHVG (NM and hybrid PHVG [7].

4. Various PHVG topology configuration

Conventional PHVG

All the three topology have similar working methodology of suddenly discharging the energy stored in the capacitor or inductor into the load.

MPHVG: The researches mostly have chosen the MPHV for corona field plasma applications, Figure 2 is the classical MPHVG, all N number of capacitors, which will get charged from low input voltage Vin parallel via resistor Rin. Across the spark gap of each stage switching action takes place which results in slight increase in the breakdown voltage over the Vin, as all charged capacitor are connected in series, breakdown voltage of each stage get cascaded to give high voltage of level N Vin [8]. both unipolar and bipolar topologies of MPHVG are commonly employed.

PFN: It can store the electric energy for long time and release the energy in short duration in the form square pulse, this feature find its application in powering laser, particle accelerator, radar etc. Figure 3 portrait the various forms of it, namely type A, B, C, D, E.
Blumlein lines PFNs: it is usually implemented for generating high voltage (HV) pulses of nanoseconds duration application, mainly in electroporation [9]. It comprise of a load connected in series with paired TL charged from HV source.it operate in two modes, charging and discharging activated by a switch as shown in Figure 4.

Fig. 4: Blumlein line PFNs

Pulsed transformer (T/F) based
It is a good choice of replacement for MPHVG as it reduces the complexity and size of the set up for the same rating , owing this advantage pulse T/F have replaced MPHVG in many of the applications . The most common form of pulse T/F are closed magnetic core T/F, air cored, open core tesla T/F, though air cored T/F attribute in the features such as low cost and simple structure, it lacks efficiency and magnetic coupling [10].open magnetic core tesla T/F exhibiting a superior magnetic coupling and HV is not often chosen as it is very costly and complex . Pulse T/F with Closed magnetic core gets attraction for its high efficiency and effective magnetic coupling at simple design and low cost . Often pulse T/F are combined with voltage multiplier as it considerably reduce the stages of voltage multiplier. Figure 5 displays the HV pulse T/F topology.

Fig. 5: HV pulse T/F topology

Power electronic converter based
Non MMC: it use power electronic configuration to boast the voltage hence need for HV switch in series is indispensable for chopping the boasted voltage before feeding into the load. It can be mainly classified into three sub categories solid state Marx generators (SMPGs), SMPS and CDVM

CDVM: it find a predominate role in the application demanding a HV and low current for several decades, for the reason of reducing the size of HV T/F, comparatively higher efficiency and less weight compare to conventional T/F rectifier ckt [11]. H bridge are usually employed to generate bipolar pulse at the output Figure 6 portrait classical CDVM.

Fig. 6: classical CDVM

SMPS: Here few basic SMPS topologies are taken for the study, the topology proposed in the Figure 7a. employ a modified flyback converter with RCD ckt across primary side of T/F and eliminating filter capacitor at output. When switch Sis turned ON primary of the T/F connected to Vin and RDC get charged, when switch Sis turned OFF it produces unipolar high voltage.

The topology discussed in the paper [12] (shown in the Figure 7b use a combination of buck-boast converter in input and pile of capacitor voltage switch at output. By controlling the switch S in series, HV pulse is feed to the load. Again here also a unipolar pulse is developed.

The topology adopted in the Figure 7c. employ front to front connected two boast converters with their load connected in such way that difference of the voltage generated by the two converters is applied across it, so that HV pulse developed here is bipolar

The topology considered shown in the Figure 7d. is proposing operating the boast converter in discontinuous mode to produce a unipolar pulse without HV switch.

SMPGs: principle behind the SMPGs is to make use of LV to charge N number of capacitor connected in parallel and...
then to produce HV pulse by connecting all charged capacitor in series [13]. Unlike MPHVG power electronic switches replaces the spark gap, SMPGs can be categorized into three sub category based on factor such as component used in the module of repeated capacitor, feature of producing uni/bi polar pulse and complexity in control.

Topology shown in Figure 8a. owns a simple structure with N number of K switch for charging the capacitor and G switch allowing the production of pulse across the load, current stress in switch K is very high near to Vin. When the Topology adopted shown in Figure 8b. compared with previous topology number of switches used is brought down, but it demand the control for charging current to isolate Vin while pulse generation. If all G switches are turned ON simultaneously it will produce a unipolar pulse.

Topology employed shown in Figure 8c. can produce bipolar pulse, but in case of previous two cases they need two stack for doing the same. This is possible as G1 turns ON capacitor charge in parallel and G2 used to produce bipolar pulse. All together the SMPGs topology discussed here need an extra passive component or special control to mitigate HV droop, at the same hand unlike MPHVG there is no need of completely discharging the capacitor. Hence switch voltage and capacitor voltage are safely clamped .

Fig. 8: Various SMPGs topologies

MMC: To build the Vout stepwise N number of sub module (SM) may be half bridge or full bridge converter are connected in series of converter arm, capacitor of each module hold a Vavg = Vdc/N. Therefore N number of SM of an converter arm can produce a Vout of N+1 level, it can produce a bipolar pulse with Vpeak = ½(Vdc). But for balancing capacitor voltage, sensors are required which increase the cost and complexity of hardware. Moreover MMC topologies proposed in have fairly reduced the cost and complexity in the hardware, but in turn it has increased the complexity in the control aspect with the increase in the number of SM. Figure 9 display the common structure and its equivalent ckt which is usually adopted with two level HB-MMC.

Fig. 9: MMC a. single phase MMC structure and b. equivalent circuit of two-level HB- MMC

Hybrid power electronics PG: Owing to the limitation of MMCHVPG such as requirement of HV DC as Vin and a leg can produce only bipolar pulse with Vpeak =1/2(Vin). To resolve the above-mentioned downside of MMC can be combined with Non- MMC power electronics based HV generators, as discussed in Combination are available as either MMC at LV input nor at the output across the load. In the Table 2 shown below the power electronic based HV pulse generator are compared based the factor such as DC supply, Foot print, modularity, pulse generated requirement of HV switch and voltage sensor.

Table 2: Comparisons between the Power Electronic based HV generating topologies

| Factor          | Non MMC | MMC      | Hybrid [13] |
|-----------------|---------|----------|-------------|
| DC supply       | LV      | HV       | LV          |
| Foot print      | Small   | Large    | Moderate    |
| Pulse generated | Rectangular | Different | Different    |
| Modularity      | Lacks   | Modular  | Modular     |
| HV switch       | Required| Not required| Not required|
| Voltage sensor  | Not required | Control is complex in the case of without sensor | Required |

5. Comparisons of Various Bipolar to PHVG

Conceptual study was made on the bipolar topologies, for the fact that bipolar topologies offers a superior result compare to unipolar topologies for all the application discussed in the section 1. along with that the solution offered by them are highly reliable and simple. As we have discussed most of the bipolar topologies in section 3, the Table 3 display the merits and demerits of few bipolar topologies which are been commonly employed in PHVG such as bipolar solid-state Marx generator, conventional MPHVG, MMC and two group of series connected HB-SM are displayed in the Figure 10.
Table 3: Merits and demerits of various bipolar PHVG

| Solid state Marx generator | Merits | Demerits |
|---------------------------|--------|----------|
|                           | - IGBTs of low voltage rating is sufficient | - IGBTs exert uneven current stress |
|                           | - LV DC is sufficient | |

| Push pull inverter | Merits | Demerits |
|--------------------|--------|----------|
|                     | - LV AC is sufficient | - Static and dynamic load sharing is required for diodes and IGBTs |

| Conventional MPHVG [15] | Merits | Demerits |
|-------------------------|--------|----------|
|                         | - LV DC is sufficient | - At the output stage of HB, series connected IGBT stack is need as HV switch |
|                         |            | - IGBTs exert uneven current stress |

| MMC [11] | Merits | Demerits |
|----------|--------|----------|
|          | - IGBTs of low voltage rating is sufficient | - HV DC is must |

| two group of series connected HB-SM | Merits | Demerits |
|------------------------------------|--------|----------|
|                                    | - Current stress is less | - While charging, to bypass the load HV back-back SCR are required across the load |
|                                    | - LV DC is sufficient | - SCR demands auxiliary protection |

6. Effect on line energizing the pulsed HV generators for plasma technology application

Primary requirement of most of the pulsed HV topologies discussed in section III are either HV/LV DC supply as the input, but in common supply from main line is AC power hence conversion of AC to DC is must. Owning to the truth that power supply for pulsed HV supply is nonlinear in nature, which would distort the source current, generated harmonic will disturb the power system link with this system. Therefore it becomes our responsibility to reduce the harmonics produced by the pulsed plasma application.

In the topology discussed in for improving the power capability resonant converter are cascaded and used along with 3 ø diode bridge diode bridge rectifier in front end for converting AC supply to DC, usually 3 ø diode bridge diode bridge rectifier are the common choice for simplicity and reliability at low cost, but the down side it pollute the main supply by pumping harmonics into it. As these harmonic drastically affect the effective functioning of other equipment linked with the same main line, the issue of harmonics originate with the fact that power consumption of pulsed HV supply are not continuous from main line, hence it becomes necessary to have some arrangement to consume power continuous from main line.

For above reason two optimizing technique is adopted for scheduling the pulse, first is the Optimal strategy (OS) which examine the HV pulse generating system by time domain analysis with the data samples collected to predict the optimal parameter for generating a pulse, that would reduce the THD to considerable level. Second optimizing technique is Empirical strategy (ES), in this technique
gaps in between the pulse are identified by an algorithm and it is packed with the pulse of other power units, so that we can ensure continuous power consumption. In the point of THD reduction, performance of OS is considerably high compared to ES. But on the other hand computational difficulties is very high.

Topology put forth in employs another common combination thyristor controlled reactor (TCR), bridge rectifier and HV T/F. again all the power electronic device employed for service becomes the source of harmonics, as a fruitful solution for above problem passive filter can be added along with the previous topologies which would reduce the THD to the considerable level as suggested in . Compared to parallel connected passive filter is better than the series connected passive filter, THD is reduced to twenty percentage when a tuned passive filter are connected in series and parallel. At the same time we can’t discard the short coming hosted by passive filter, such as its performance completely rely on the impedance of source which is unknown in most of the case and again the nature of passive filter to go in parallel or series resonance with input is the reason for triggering harmonics.

Again in case of loads being dynamic in nature only active or hybrid filter will offer better performance compare to passive filter. The topology of multi pulse T/F with 12 pulse converter in cascaded mode for getting modular structure, modular structure offer proper load sharing and aids them eliminating harmonics of order 5th and 7th. Thereby THD was brought down to 13% with a more simple and reliable topology, in spite all these merits topology is not popular due the drawbacks caused by use of multi pulse T/F such as consumption of more power, bulky, heavy and high cost.

The other Solution suggest in the context of reducing harmonics is to adopt the active filter with six switches (Vienna converter) as the front-end converter offer a balanced loading on the phases of main and also bring down the THD to 4.02%. If the shunt active filter alone with the rectifier employed it can process about sixty eight percentage of reactive power thereby bring down the THD to 2.1%, the topology put forth in the same article is employing shunt active filter along with Vienna converter bring down the THD to very low value of 1.48%, again the active filter offers a reliable performance even if load is under dynamic condition. On the other hand we have to forego the downside such as due to active filter complexity and cost increase. Due to pulsed T/F making the system bulky, heavy and expensive.

The topology put forth in the article [14] argue the implementation of high frequency switched mode power supply HF-SMPS, spot light on the fact that in the conventional topologies operating with rectifier and low frequency T/F working at power frequency generate large amount ripples of low frequency. The proposed HF-SMPS will be a very good replacement for multi pulse transformer based topology which discussed previously for the following reason.

(i) Reduction in size and volume
(ii) High power factor of around 0.9
(iii) It doesn’t depend on input frequency
(iv) Very less ripple content

In addition to this strategy adopted in the article [14] such novel centred current control and replacing IGBT switches with MOSFET aids in improving the efficiency to ninety eight percentage and in reducing the THD. The novel centred current control reduces the current in the resonant tank, which in turn brings down the switching loss.

7. Topologies for avoiding Back corona effect

Back corona phenomenon occurs in the most of the pollution control application of plasma technology, especially this cause a serious problem in the collection efficiency of ESP. this phenomenon occur mainly if flue gas is carrying high resistive particle, when corona current between the electrode pierce the surface of the particle. High resistivity of the particle leads to high voltage drop across the particle, this high voltage drop is sufficient to cause electrical discharge producing positive ion and negative ion.

The positive ion moves in opposite direction to collecting electrode, this is what termed as back corona. As solution several proposal are put forth opting changes in the design and operation such as employing hole ESP , electro hydrodynamic ESP, wet type ESP where resistivity of particle doesn’t have any influence as the electrode are washed with water, ESP applying high temperature around 150 degree Celsius to the flue gas at very high temperature particle in the flue gas experience a decrease in the resistivity and in recent low temperature ESP flue gas temperatures are brought down to 90 degree Celsius at that point water and Sulphur dioxide starts to condense back there by reducing the resistivity [15].

This article mainly concentrates on the solution offer by electrical power supply topologies, the topologies proposed employs intermittently rectified half wave to power the ESP for the reason that during the dormant period there will be a decrement in the charge available in the surface of dust in this way the back corona can be avoided.

From the article we can clearly infer that in intermittent and pulsed power ESP by improvising the HV generator back corona can be minimized, even then these topologies are attractive due the reason of comparatively less efficient the DC powered ESP. All this happen due the fact that dominant period is longer than HV applied period [16], as solution for above problem asymmetrical rectangular AC voltage is used to power the ESP discharge electrode. Here application of positive and negative voltage is asymmetrical in nature, as the positive voltage are applied for quiet longer time compared to negative voltage.

8. Conclusion

The article present the classification and comparison of various pulsed high voltage topologies employed in cold plasma technologies, the comparison insight the benefits and drawbacks of each topologies which would aid the researchers in selecting the topologies as per their requirement. In addition the study reveals that bipolar
topologies are simple, reliable and offer superior result compared to unipolar topologies. From the review on back corona effect we could clearly infer that if the discharge electrode are powered by intermittent or pulsed power supply or asymmetrical rectangular AC voltage can minimize the back corona effect to greater extent. Article emphasis the need of selecting the topologies and auxiliary filters which would reduce the distortion created in the supply main due to the pulsed HV generator.

References

[1]. Ahmed Elserougi, Ahmed M. Massoud, A. M. Ibrahim and Shehab Ahmed, A High Voltage Pulse-Generator Based on DC-to-DC Converters and Capacitor-Diode Voltage Multipliers for Water Treatment Applications, IEEE Transactions on Dielectrics and Electrical Insulation, August 2015

[2]. L. Barsotti & P. Merle J. C. Cheftel Food processing by pulsed electric fields, Physical aspects: Food Reviews International, Vol 15, No 2, Pages 163-180

[3]. Akinori Zukeran; Shogo Inoue; Daiki Ishizuka; Takayuki Kanek, Energy saving effect of high electric field on an electrostatic precipitator for air borne particle, 2019 IEEE Industry Applications Society Annual Meeting, November 2019 DOI: 10.1109/IAS.2019.8912413

[4]. Dan M. Goebl and Ira Katz, Fundamentals of Electric Propulsion: Ion and Hall Thrusters, JPL SPACE SCIENCE AND TECHNOLOGY SERIES, March 2008.

[5]. Leandro Buchmann and Alexander Mathys, Perspective on Pulsed Electric Field Treatment in the Bio-based Industry, Frontiers in Bioengineering and Biotechnology, October 2019, Volume 7, Article 265.

[6]. James C. Weaver, a, Kyle C. Smith, a,b Axel T. Esser,a Reuben S. Son,a and T. R. Gowrishankara, A brief overview of electroporation pulse strength-duration space: A region where additional intracellular effects are expected, Bioelectrochemistry, 87: 236–243, 2012 Oct.

[7]. Stefania Romeo, Claudio D’Avino, Olga Zeni, A Blumlein-type, Nanosecond Pulse Generator with Interchangeable Transmission Lines for Bioelectrical Applications, IEEE Transactions on Dielectrics and Electrical Insulation •1224-1230, August 2013.

[8]. M. R. Delshad, M. Rezanejad, and A. Sheikholeslami, "A new modular bipolar high-voltage pulse generator," IEEE Trans. Ind. Electron., vol. 64, no. 2, pp. 1195–1203, 2017.

[9]. A. Elserougi, A. M. Massoud, and S. Ahmed, "A boost-inverter-based bipolar high-voltage pulse generator," IEEE Trans. Power Electron., vol. 32, no. 4, pp. 2846-2855, 2017.

[10]. H. Canacsinh, J. F. Silva, and L. M. Redondo, "Dual resonant voltage droop compensation for bipolar solid-state Marx generator topologies," IEEE Trans. Plasma Sci., pp. 1-7, 2018.

[11]. L. L. Rocha, J. F. Silva, and L. M. Redondo, "Seven-level unipolar/bipolar pulsed power generator," IEEE Trans. Plasma Sci., vol. 44, no. 10, pp. 2060-2064, 2016.

[12]. A. Darwish, M. A. Elgenedy, S. Finney, B. Williams, and J. R. McDonald, "A step-up modular pulse generator based on isolated input-parallel/output-series voltage-boosting modules and modular multilevel sub-modules," IEEE Trans. Ind. Electron., vol. 66, no. 3, pp. 2207-2216, 2019.

[13]. M. A. Elgenedy, A. M. Massoud, S. Ahmed, and B. W. Williams, "A high-gain, high-voltage pulse generator using sequentially charged modular multilevel converter submodules, for water disinfection applications," IEEE Journal. Emerg. Select. Topics in Power Electronics, vol. 6, no. 3, pp. 1394-1406, 2018.

[14]. Pedro J. Villegas, Juan A. Martin-Ramos, Juan D. Martinez, Miguel J. Prieto and Alberto M. Pernia, A Digitally Controlled Power Converter for an Electrostatic Precipitator, Energies, 10, 2150, 2017.

[15]. Ahmed Elserougi, Ahmed Massoud, and Shehab Ahmed, Conceptual Study of a Bipolar Modular High-Voltage Pulse Generator with Sequential Charging, IEEE Transactions on Dielectrics and Electrical Insulation, December 2016.

[16]. Tomoya Mitsui, Akinori Zukeran, Member, IEEE, Koji Yasumoto, Takashi Nakano, Koyu Tsubouchi, and Takashi Ogawa, Prevention of Back Corona Discharge in an Electrostatic Precipitator Using Asymmetrical Rectangular AC Voltage, IEEE Transactions on Industry Applications, vol. 55, no. 6, 6287-6292, November/December 2019.