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Electrical systems for pulsed electric field applications in the food industry: An engineering perspective

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A R T I C L E I N F O

Keywords:
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Treatment chamber

A B S T R A C T

Background: Pulsed electric field (PEF) is an attractive and efficient non-thermal technology that can advance functionality, extractability, and retrieval of nutritionally beneficial compounds. For industrial PEF food processing, high electric field consistency is of importance for continuous operation and an economical return-of-investment within a short period.

Scope and approach: The technology uptake at an industrial scale is still low due to the shortage of reliable and more practical electrical systems. Therefore, designing an application-specific and cost-effective electrical system is essential for commercial use of this novel technology. This review describes the requirements and developments of the electrical systems employed in PEF food processing.

Key findings and conclusion: The process parameters and control variables of the PEF system are not only critical for the designing of the electrical systems but also for the experts of the food sciences. Inadequate or insufficient description of different engineering aspects of experimental procedures is a hindrance in allowing the work to be reproduced in other laboratories. This review describes the critical process parameters and the designing methodology of the specialized equipment required in food processing as a guide for the designers and the researchers of this technology.

1. Introduction

Sustainability concerns about the world's food supply are nothing new for the food industries. The food industries find it critical to develop processing technologies, which simultaneous preserve and advance the nutritious value of foods and create the bio-accessible compounds. The food industry is paying more attention to discover innovative non-thermal processing technologies, such as pulsed electric fields (PEF), ultrasound, high hydrostatic pressure, pulsed light and ultraviolet radiation, which process the food with minimal nutrient loss compared to conventional thermal processing (Li & Farid, 2016; Aadil et al., 2015; 2018, 2020).

PEF-based processing is an environment-friendly technique; that can be applied effectively in many food processing applications such as microorganism/enzyme inactivation, recovery of bioactive compounds, dehydration and freezing etc. (Li & Farid, 2016). Many studies have been reported on the application of PEF technology for the processing of some liquid, semi-liquid, solid, and muscle foods (Barba, Zhu, Koubaa, Sant'Ana, & Orlien, 2016; Bhat, Morton, Mason, & Bekhit, 2018). Table 1 shows the applications of PEF for diverse food processing techniques.

This technology has been utilized to inactivate different microorganisms and enzymes or reduce their activities in milk products, egg products, juice, and other liquid foods to ensure safe and appropriate

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food quality that meets consumer's demands (Kempkes & Munderville, 2017). Due to the low energy absorbed during PEF preservation, the temperature of the treated food remains low compared to conventional pasteurization techniques (Timmermans et al., 2019). PEF has also been utilized for the pretreatment of solid foods, such as apple, eggshells, potato, and muscle foods (Barba et al., 2016; Bhat et al., 2018). PEF technology has increased the efficiency and yield of the extraction process, such as the extraction of sugar from beetroot, juice from grapes or apple, and bioactive compounds (Gómez et al., 2019; Redondo, Venturini, Luengo, Raso, & Arias, 2018). Similarly, PEF pretreatment showed significant effects on process performance characteristics during the manufacturing of French fries on an industrial scale (Fauster et al., 2018). The application of PEF on beef muscles reduces shear force and improved tenderness (Bekhit, van de Ven, Suwandy, Fahri, & Hopkins, 2014). PEF also effects on the kinetics of drying and reduction of drying time is beneficial for the retention of bio-compounds in dried samples (Parniakov, Bals, Lebovka, & Vorobiev, 2016). Hence, PEF-based processing contributes to significant improvements in this industry.

The efficiency of PEF to permeabilize cell membranes based on process parameters (electric field strength, treatment time, specific energy, pulse shape, pulse width, frequency, and temperature), treated food sample (pH and conductivity), and target cells (size, shape, membrane, and envelope structure). Transmembrane potential 'U_m' in (V) generated by an external electric field for a spherical cell can be calculated as:

$$U_m = 1.5\ r\ E \cos\theta \tag{1}$$

Where 'r' radius of the target cell in (μm), required electric field strength 'E' in (kV.cm^{-1}), and the orientation 'θ' (degree) of the target cell in the electric field. PEF food processing is effective when the applied electric field induces voltages across the cell's membrane 'U_m' exceeds the critical transmembrane potential 'V_c' (0.5–1 V). The required critical potential and energy is dependent upon the sample food and processing technique (Barba et al., 2015; Mahnič-Kalamiza, Vorobiev, & Miklavčič, 2014).

The external electric field increases the transmembrane potential and initiates the pore formation in the membrane of the biological cell (plant, animal, microbial, and algae). Once pores are created in the order of 0.5 nm radius, they may expand as a result of the applied electric field, and the flow of material into and out of the cell will be disrupted (Sale and Hamilton, 1967). The loss of the membrane integrity results in the cell contents diffusion into their surroundings and causes the death of the living cell, called irreversible electroporation (Gavahian, Chu, & Sastry, 2018). Reversible electroporation, after removal of the external electric field, retains the cell alive. Both of these types have been used in the different applications of food processing (Table 1).

PEF technology could enable the food industry to produce high-quality food products due to the following advantages:

i. Effective preservation of liquids with low ionic strength and low conductivity;
ii. Produces high yield and better quality during the extraction of juice and oils
iii. Enhances mass transfer in drying processes of fruits, meat, and fish at a lower temperature (Liu, Grimi, Lebovka, & Vorobiev, 2019a)
iv. Pigment extraction can be achieved at lower temperatures
v. Positive impact on faster digestion of proteins
vi. PEF has a softening effect that reduces the energy needed for cutting (Ignat, Manzocco, Brunton, Nicoli, & Lyng, 2015)
vii. Minimizing temperatures rise and reducing processing times (Chotphruethipong, Aluko, & Benjakul, 2019)
viii. Energy-efficient and environmental-friendly (Jambrak, Djekić, & Van Impe, 2018)
ix. Less processing cost
x. PEF improves process efficiency when it is combined with other techniques, such as thermal, high hydrostatic pressure and ultrasound and make it possible to achieve better outcomes than using individual process alone (Katiyo, Yang, & Zhao, 2017).

Despite the benefits of PEF in the food industry, there are some limitations too that hinder the uptake of the technology. For example, the shortage of reliable and more practical electrical systems is acknowledged as the main limitation for commercial uptake of the technology (Priyadarshini, Rajauria, O'Donnell, & Tiwari, 2019). However, other limitations for PEF-based food processing are:

i. High capital cost (Priyadarshini et al., 2019)
ii. Ineffective against some enzymes and spores (Wang, Pyatkovskyy, Yousef, Zeng, & Sastry, 2020)
iii. Challenging to use with conductive materials
iv. Bubble generation and dissolved gases are the operational problem and cause dielectric breakdown
v. Inadequate economic and engineering studies for the up-scaled process
vi. Limited defined protocols for food processing

This review describes recent developments in the engineering aspects of the technology with the main focus on the electrical system employed in PEF-based food processing. A brief description of process parameters, designing of the treatment chambers, and pulsed power generators are provided to engage the non-expert readers and provide

Table 1
Role of PEF based processing in the food industry.

Application	Optimum Electric field range	Optimum energy	Optimum Pulse width	Type of electroporation	Sample foods	References
Liquid food preservation	2–30 kV cm^{-1}	10–200 kJ kg^{-1}	1–20 μs	Irreversible	Milk, liquid white egg and fruit juices	(Buckow et al., 2013; Izabelanair, 2018)
Enzyme deactivation	10–70 kV cm^{-1}	100–250 kJ kg^{-1}	1–20 μs	Change the secondary structure	Fruit juices	(Mannozzi et al., 2019; Liang, Zhang, & Lin, 2017)
Extraction	0.5–5 kV cm^{-1}	1–15 kJ kg^{-1}	10–100 μs	Ireversible	Fruits, seeds and sugar-beet	(Barba et al., 2016; Ferreira et al., 2019)
Bio-active compounds recovery	0.5–8 kV cm^{-1}	1–80 kJ kg^{-1}	100−50,000 μs	Reversible	Fruits and vegetables	(Luengo & Raso, 2017; Ferreira et al., 2019)
Meat processing	2–3 kV cm^{-1}	5–20 kJ kg^{-1}	20–100 μs	Reversible	Beef, chicken, fish and pork	(Astráin-Redín, Raso, Cebrián, & Álvarez, 2019; Bekhit et al., 2014)
Dehydration	0.2–3 kV cm^{-1}	1–20 kJ kg^{-1}	20–200 μs	Reversible	Fruits and vegetables	Astráin-Redín et al. (2019)
Wine processing	3–12 kV cm^{-1}	0 1–10 kJ kg^{-1}	10–100 μs	Reversible	Cabernet, riesling, sauvignon, aglianico	(Saldaña et al., 2017; Barba et al., 2016)
Pre-sowing seeds treatment	0.5–2 kV cm^{-1}	0.24–0.96 kJ kg^{-1}	20–200 μs	Reversible	Wheat, soybean and sunflower seed	Starodubtseva, Livinskiy, Gabriyelyan, Lubaya, and Afanacev (2018)

sufficient background. Moreover, it provides some guidelines and principles to understand the operation of the process and suggests the future development needs of these electrical systems.

2. PEF processing system

A general electrical system for PEF processing is shown in Fig. 1. It contains a treatment chamber, pulsed power supply, and control & monitoring system (Buchmann, Bloch, & Mathys, 2018). A pulse power generator is applied to deliver the pulsating high-voltage across the treatment chamber containing the food (Sack and Mueller, 2017). The pulse power generator is a combination of any passive discrete elements (capacitive, inductive, and resistive), transformers, and power switches (Elgenedy, Darwish, Ahmed, & Williams, 2017; Kumar, Vijayalakshmi, Kathiravan, & Nadanasabapathi, 2019). Power switches are required to transfer the energy stored in the capacitors or magnetic fields of inductors (Redondo, 2017, pp. 1–21). Transferring this energy in a financially affordable way is very important (Kempkes & Munderville, 2017*)* and can impact the whole electrical design of this technology.

Each part of the PEF system has numerous associated parameters (Fig. 1) that influence the processing conditions for a desired application and food sample. Effective process performance can be achieved by the analysis and subsequent adjustment of these process parameters (Puértolas & Barba, 2016). These parameters are crucial for the effective use of this technology to a commercial level. The key process parameters are electric field strength, flow rate, pulse waveform, pulse repetition rate, exposure time, specific energy density, and temperature variation in the treated sample (Amit, Uddin, Rahman, Islam, & Khan, 2017). Fig. 2 elaborates on the interdependency/complexity of these process parameters and variables as well as shows the difficulty of modifying a process parameter without disturbing other process parameters.

Published literature offers several examples of using these parameters that may be used as a starting point for the development of novel applications, but they cannot be used without further optimization for a particular application and food sample (Liu, Oey, Bremer, Carne, & Silcock, 2017). Research work has done to estimate the optimized process parameters for a specific PEF food application through a statistical approach (Kathiravan, Nadanasabapathi, & Kumar, 2013). However, these post-processing techniques help to calculate the optimized parameters but cannot be used to start or design an experimental setup.

The process parameters can be analyzed and compared in terms of the required treatment intensity or the required energy consumption. Fig. 2 also shows the design steps in a numerical order to calculate the process parameters for the specific application/product. The optimization of these parameters can be done by keeping a few parameters as a constant, and the rest dependent parameters can be calculated through the sequence presented in Fig. 2. The development of an optimal treatment protocol is critical to ensure a visible upscaling of the process (Gagneten, Leiva, Salvatori, Schebor, & Olaiz, 2019). Furthermore, it will also facilitate understanding and writing the research work related to this technology.

2.1. Treatment chamber

From an electrical perspective, the treatment chamber denotes the electrical load comprising of the electrodes and the sample food material (Esplugas, Pagan, Barbosa-Cánovas, & Swanson, 2019). The treatment chamber plays a significant role in the success of PEF-based food processing. For instance, the peak field intensity, treatment homogeneity, and subsequently, the process efficiency is all affected by the design of the treatment chamber (Masood, Diao, Cullen, Lee, & Trujillo, 2018; Zhu et al., 2017). Key considerations for the design of the treatment chamber are the shape of the insulator and the configuration of electrodes (Esplugas et al., 2019). To optimize treatment capacity, flow pattern, and electrical impedance, some principals need to be followed (Masood et al., 2018). The principles needed for the designing of the treatment chamber are:

I. The removal of any direct contact between the electrodes and the sample food is preferred, particularly for liquid food, to prevent electrolysis due to electrochemical reactions (Pataro, Barca, Donsì, & Ferrari, 2015). However, the use of an insulator between the electrodes is energy wastage as it develops a capacitor that needs to be charged and discharged with each pulse (Austin, Holden, Hinz, & Conley, 2017). Thus, to improve energy efficiency, liquids must come in contact with the electrodes.

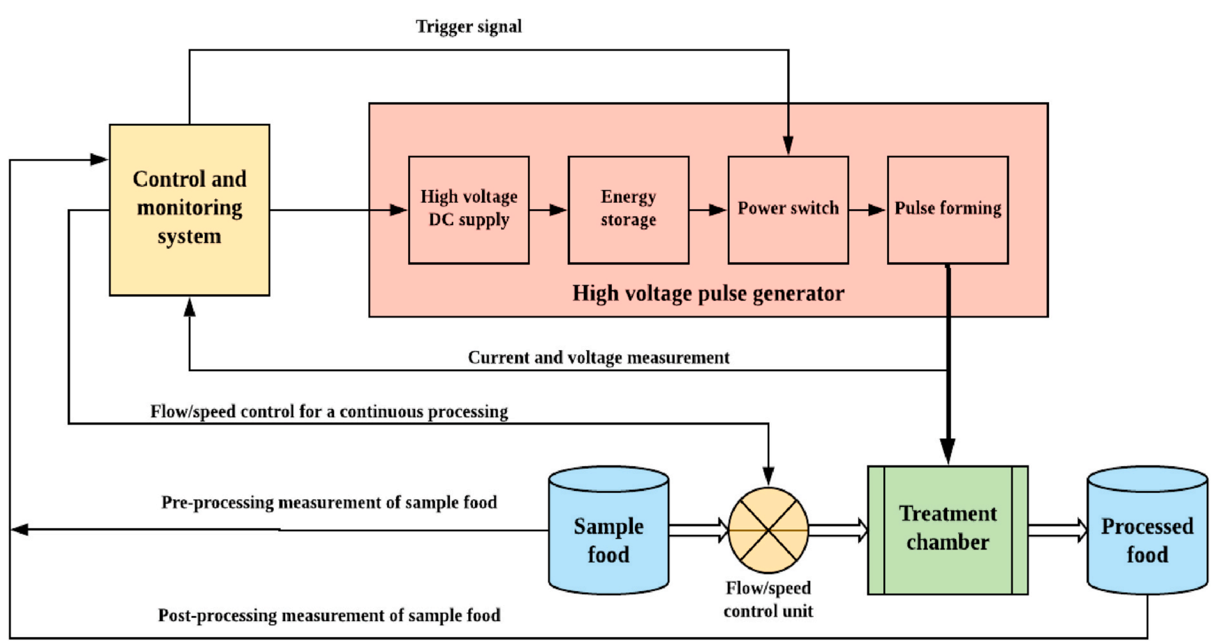


Fig. 1. Schematic diagram of a general PEF-based food processing system; shows three major parts of the system, high voltage pulse generator (red), treatment chamber (green), control & monitoring system (yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

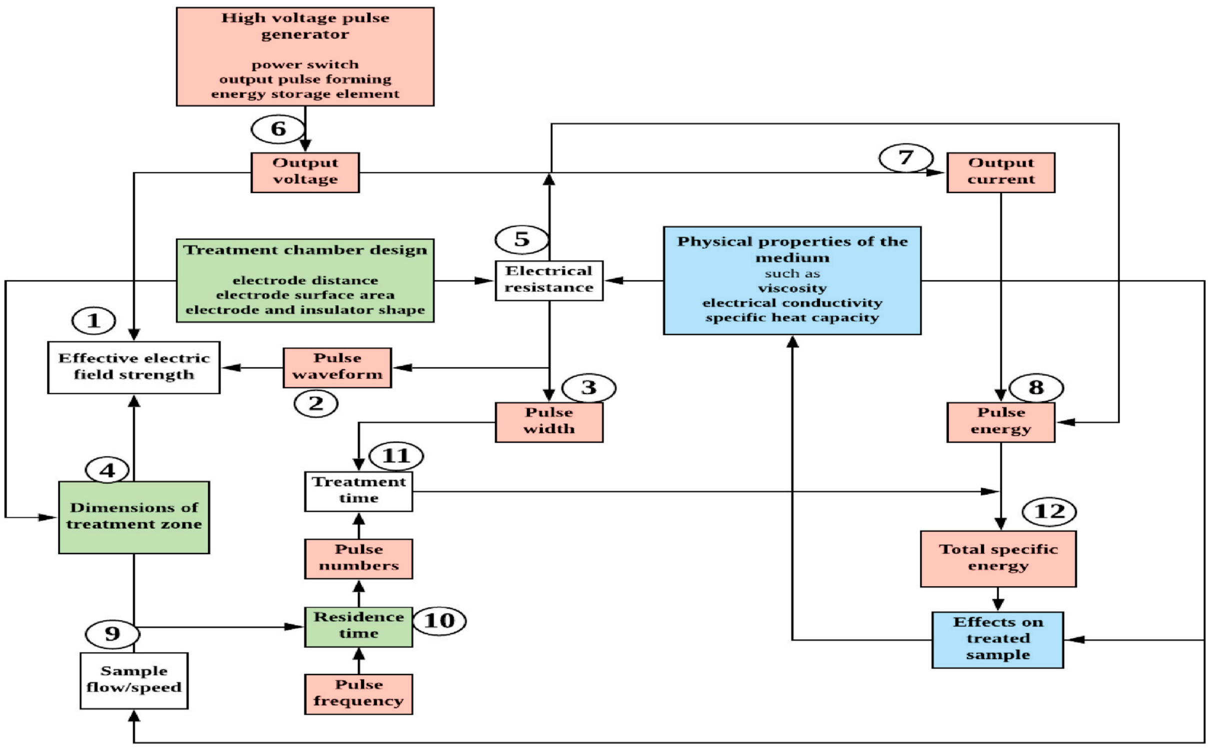


Fig. 2. Flow chart describes the interdependence of PEF-based food processing parameters associated with each part such as, high voltage pulse generator (red), treatment chamber (green), and food sample (blue). Flow chart also carry numbering to understand the design steps associated with each application and food sample. Step # 9 is only applicable for continuous systems. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

II. Sharp-edged electrodes may produce arcing as the surface charge density (charge per unit area) of the sharp edge is much larger (Knoerzer, Baumann, & Buckow, 2012). Round-shaped electrodes are preferred more than sharp-edged electrodes to reach maximum electric field intensity.

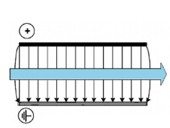
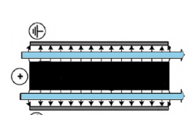
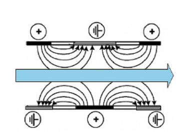
III. The compensation of the electrode's thermal effect is another feature to be considered. A proper geometry of electrodes with a cooling system should be considered (Saldaña et al., 2017). However, it is not essential in a continuous moving/flowing food sample. The temperature rises significantly higher in laminar flow conditions relative to turbulent flow conditions (Pataro, Senatore, Donsì, & Ferrari, 2011).

IV. The dielectric breakdown strength for gases (30 kV cm^{-1} at atmospheric pressure) is considerably lower than fluids. It may cause the electric field to go beyond the dielectric barrier of the gas bubbles and produce partial discharge (Ramaswamy and Ramachandran, 2016). Hence, it is essential to use a pressure releasing device/ultrasonic degassing to avoid such dielectric breakdown.

2.2. Configurations of PEF treatment chambers

Batch and continuous are two major categories of the treatment chambers. Batch chambers can only process a given volume of liquid and solid foods. However, a dynamic chamber can achieve the same productivity found with conventional continuous processing of liquid samples required in industrial applications. Parallel, coaxial, and co-linear electrodes are common configurations of electrodes used in PEF (Huang & Wang, 2009; Kandušer, Belič, Čorović, & Škrjanc, 2017). Table 2 shows the common characteristics of various electrode

Table 2
Common characteristics of various electrode configurations.

Characteristics	Parallel plate	Coaxial	Co-linear	References
Liquid flow with the direction of the electric field	Right angle	Right angle	Parallel	Bermaki et al. (2017)
Electric field distribution	Uniform	Almost uniform at large radii	Non-uniform	(Morales-de la Peña et al., 2017)
Mathematical calculation for the average values of electric field strength	$\frac{V}{d}$ Where V = applied voltage; d = gap between electrodes	$(V)/\left(rln\left(\frac{R_o}{R_i}\right)\right)$ *Ro* and *Ri*R_o and R_i are outer and inner radii respectively; $R_i < r < R_o$	Not possible but can estimate through numerical analysis	Masood et al. (2018)
Number of electrodes	Maximum = 2	Maximum = 2	Minimum = 2 with an insulator	Sack & Mueller et al. (2017)
Electrical resistance	Low (ohms)	Low (ohms)	High (hundreds of ohms)	(Novickij et al., 2016; Toepfl et al., 2007)
Cross-sectional geometry with a continuous flow of liquid food				(Toepfl, Siemer, Saldaña-Navarro, & Heinz, 2014)

configurations. Electrodes with parallel plates configuration provide the most uniform electric field distribution irrespective of edge effects if the gap between the electrodes is not considerably greater than their electrode area. In this configuration, the large effective area of the electrodes produces a low electrical resistance in the treatment chamber (Masood et al., 2018). Low electrical resistance may cause corrosion of the electrode at the interface of the electrode and treated liquid and releasing of minerals from the electrodes to the treated food. Two electrodes are most commonly recommended in this configuration, but four electrodes can also be placed on the sidewalls of a square treatment chamber with an insulator placed between every two electrodes. Each pair of the adjacent plates forms electrodes and produces biaxial electric field lines (Bermaki et al., 2017). However, this latter configuration does not seem to add significant advantages compared to only two electrodes configuration.

Co-linear electrode configurations contain multiple electrode rings on alternating potentials isolated by insulating rings (McHugh & Toepfl, 2016). Co-linear chamber, as shown in Table 2; is composed of three conductors and two insulators. Heterogeneous distribution of the electric field strength and the temperature is controlled by the physical design of the insulator that is positioned between the electrodes. This configuration of electrodes provides large treatment capacity and lower effective cross-sectional area of the electrodes, which develops a high impedance that is advantageous for continuous food treatment (Góngora-Nieto, Sepúlveda, Pedrow, Barbosa-Cánovas, & Swanson, 2002). This design requires low current from the pulse modulator, which is a favorable feature in PEF systems. This design produces some non-uniform electric field distributions in under-treated regions (often in central regions or dead spaces) and needs a higher voltage to cover these regions.

The coaxial chamber is composed of two hollow cylinders with the direction of the electric field points radially, whereas the sample food moves axially. In this configuration, the distribution of the electric field decreases radially from the internal towards the external cylinder. However, the higher the radius of the electrodes (at a given gap), the more homogeneous is the electric field distribution. The impedance of the treatment chamber is controlled by the conductivity of the liquid food and also changes the output waveform of the pulse generator. This resistance variation is an inevitable obstacle to the advancement of the PEF treatment system (Huang & Wang, 2009). This limitation can be overcome in the coaxial chamber design by adjusting the position of the internal electrode that permits different values of resistivity (Alkhafaji & Farid, 2007). A temperature rise of the treated sample occurs mostly due to two main reasons, Joule heating and arcing. This configuration can be used at high electric field intensities with less temperature increase of the treated material (Huang, Yu, Gai, & Wang, 2013; Masood et al., 2018). This low-temperature rise is due to the absence of arcing that it is often accompanied by heat.

Table 3 summarizes the applications of various treatment chambers used for PEF-based foods treatment. Most of the published research has investigated the influence of PEF treatment of liquid foods with a parallel plate configuration of electrodes at the bench scale (Table 3). However, this configuration has some limitations; coaxial and collinear are appropriate alternatives.

After such extensive research with PEF processing; the market for PEF systems is no longer limited to small laboratory/R&D units. Diversified Technologies, Inc., PurePulse Technologies, Inc in the USA, Pulsemaster B.V. in Netherlands, Energy Pulse Systems in Portugal, Elea-Technology in Germany, and ScandiNova Systems AB in Sweden have already developed industrial equipment to facilitate PEF-based food processing. However, food processing research with these industrial systems has not been widely reported as compared to the bench-scale system. There is a need to direct future research towards continuous processing mode to meet industrial requirements and ensure commercial acceptance. It requires substantial funding and research collaboration among various research groups to support this research scope.

2.3. *Electrical resistance of the treatment chamber*

The electrical resistance of the treatment chamber controls the output of the pulse generator. Dimensional characteristics of the electrodes and the electrical conductivity of treated liquid are the main parameters responsible for the electrical resistance of the treatment chamber. The electrical characteristics of electrodes are also affected by the physical properties of the electrodes, such as surface roughness and contamination by biological materials such as protein or fat deposits (Moonesan and Jayaram, 2013). A parallel combination of resistance and a capacitor is the electrical equivalent model for a treatment chamber containing liquid food (Krishnaveni, Subhashini, & Rajini, 2017). A single resistance can replace this electrical model as the value of resistance is much lower than capacitance. Table 4 shows the calculation of the capacitor and resistor for coaxial and parallel configuration of electrodes.

From the above equations, it can be seen that the capacitance of the load is independent of the conductivity, whereas resistance varies with conductivity. Co-linear treatment chambers, along with a small electrode surface area and a large insulator, offer high electrical resistance loads (Sack & Mueller, 2017). As a result, it requires a low current, which is favorable for the development of pulse modulator on large-scale food treatment.

2.4. *Materials for fabrication*

For food treatment, both electrodes and treatment zone should be

Table 4
Equivalent resistance and capacitance of treatment chambers.

Configuration	Resistance	Capacitor
Parallel Plate	$R = \sigma\frac{d}{A}$	$C = \frac{\varepsilon_o\varepsilon_r A}{d}$
Co-axial	$R = \frac{\ln(ro/ri)}{2\pi\sigma l}$	$C = \frac{2\pi\varepsilon_o\varepsilon_r l}{\ln(ro/ri)}$

Table 3
Treatment chambers fabricated for PEF treatment of liquid foods.

Experimental/ Simulation	(Continuous/ Static) mode	Electrodes configuration	Material of electrode	Material of Insulator	Capacity	Dimension of the treatment zone	References
Experimental	Batch	Co-linear	Aluminum	Acrylic	1 mL	$10 \times 5 \times 2$ mm; gap = 1 mm	Krishnaveni et al. (2017)
Experimental	Continuous	Coaxial	Stainless Steel	No insulator	2 mL	Gap = 1.27 mm	Moonesan and Jayaram (2013)
Experimental	Batch	Parallel plate	NA	No insulator	375 mL	$150 \times 25 \times 100$ mm	Kayalvizhi, Pushpa, Sangeetha, and Antony (2016)
Experimental	Batch	Parallel plate	Stainless Steel	No insulator	3 mL	50×60 mm; gap = 1 mm	Qin et al. (2015)
Experimental	Batch	Parallel plate	NA	Not available	100 mL	100 mm; gap = 100 mm	Sack et al. (2015)
Simulation	Batch	Parallel plate	Stainless Steel	No insulator	5 mL	11 mm; gap = 30 mm	Parniakov et al. (2016)

designed with electrochemically inert material of food-grade, easy to clean, and sterilizable. Corrosion, erosion, and mechanical fatigue are the main reasons for the structural failure of the electrodes. Hence, the life of any electrodes depends on the material and current density (Novac et al., 2014). With long operational time (aging) of the small PEF system, the electrodes release particles in the treated samples (Gad, Jayaram, & Pritzker, 2014). Hence, it is necessary to record the use of treatment chambers alongside the operational parameters and calculate its life cycle. This problem can be overcome with the use of some insulating materials as a treatment zone inside the electrodes, but this can lead to energy waste. Hence, for safety, it is essential to replace the electrodes after the expiry of their life cycle. However, in large PEF systems, the small amounts of the electrode material are entered into large volumes of fluid (negligible particle.volume^{-1} ratio), and these very low values may be tolerable (Pataro & Ferrari, 2017).

Initially, PEF electrodes were fabricated from carbon (graphite), to avoid any contamination of the treated product. Unfortunately, these electrodes have very short lifespans (Tokusoglu and Swanson, 2014). The best materials for electrode manufacturing are precious metals (gold, platinum, etc.), which have very low resistance and minimal erosion at high currents. However, stainless steel is considered suitable and economical electrode materials due to their high corrosion resistance and realistic prices (Toepfl, Heinz, & Knorr, 2007). Stainless steel is also safe as it does not release toxic materials (Geng and Lu, 2013). Most of the commercially available PEF processing systems utilize electrodes made of stainless steel, aluminum, gold-plated, and silver (Barbosa-Cá novas et al., 2004). Polyvinyl chloride (PVC), pyrex-glass, polyetherimide, polypropylene, and polysulfone have been recommended as treatment materials (insulators).

2.5. Coating of electrodes

The presence of an oxidized layer may reduce the apparent erosion rate of electrodes in some cases. However, the coated electrodes with layers of corrosion-resistant materials do not tolerate high voltage as well as current values under PEF conditions. The coated material isolates the electrodes from the sample to be treated and can also overcome the Joule effect in the PEF treatment by controlling the conduction current (Novac et al., 2014). However, treatment with coated electrodes requires the application of higher voltage to attain the same field strength in the product.

2.6. Flow rate inside the treatment chamber

The flow rate of the treated food is an essential parameter in PEF processing and plays a significant role in the designing of the treatment chamber as well as the pulsed power supply. The volumetric flow rate is the amount of fluid (volume) that flows through a control volume per time unit. The rate of flow or velocity of a sample is related through the cross-sectional area of the treatment zone. Some research groups have studied the effects of the flow rate with different geometries of the treatment zone (Knoerzer et al., 2012). Liquid flowing through the small cross-sectional area has a higher velocity. Low peak power from the pulse power supply is required to treat this flowing liquid but requires high frequency due to the high velocity of liquid (Huang et al., 2013; Kandušer et al., 2017).

The flow velocity profiles define the residence time inside the treatment zone and, consequently, overall changes that occur in the treated food. Although extended treatment times are favorable for the inactivation of microbes, it also increases the Joule heating effect (at constant pulse frequency and electric field strength). It could negatively affect other quality attributes (Stankevic et al., 2020). Additionally, hindrances in the confined flow profile due to the design of the chamber can develop a residence time distribution in which some portions of the sample are over-processed, whereas rest are under-treated (Buchmann et al., 2018). Hence, a uniform distribution of the velocity profile confirms homogeneous treatment and temperature distribution.

If the flow of the liquid is laminar, there is a possibility that heterogeneous treatment will likely occur (Buchmann et al., 2018). To provide a pre-determined amount of energy per unit volume, a pulse modulator with high power, as well as a high frequency is required to accommodate the laminar flow (Raso et al., 2016). The exposure of particles (e.g., microbial cells or suspended solids such as in milk) to different locations in the treatment zone with different electric field strengths is only possible by increasing the mixing effects, and the creation of turbulence at low flow velocities may offer such required intense fluid mixing. It eventually may lead to a more homogeneous distribution of temperature and electric field to the whole treated sample.

Turbulence is mainly required for PEF processing to guarantee that the microorganisms are exposed to effective electric field strength require to inactivate at different angles (Novac et al., 2014). Additionally, turbulent flow leads to greater particle friction that also increases the heat transfer in contrast to the laminar flows (Buchmann et al., 2018). Hence, it is mandatory to create artificial turbulence inside the treatment chamber. This artificial turbulence can be achieved by modifying the inlet to produce turbulance or inserting some physical obstacle in the treatment zone (Kandušer et al., 2017) to alter the laminar velocity profile of liquid flow into a turbulent one. However, these static mixing devices complicate the washing and maintenance procedures of the system.

2.7. Requirements for numerical simulation

A comprehensive understanding of the electric field and temperature distribution in the treatment chamber is important to achieve greater efficiency of a PEF treatment and strike a balance between energy input and achieving a high-quality product (Huang et al., 2013). However, the relative sizes of the treatment chambers compared to the temperature measurement instruments represent a challenging case to execute suitable measurements at various locations within the treatment chamber without disturbing the flow. Simulation modeling is a substitute for experimental work or an alternate method when experimentation is difficult or impossible and could be very beneficial to overcome this obstacle (Zhu et al., 2017).

Ideal PEF treatment requires a uniform electric field with short pulse duration and high repetition rate (Toepfl et al., 2014). However, individually applied pulses are typically so short (μs) so that the fluid sample could be considered essentially static during the application of a pulse, and subject to all the non-uniformity inherent in the chamber design (Kandušer et al., 2017). Hence, multiple pulses must be applied during the fluid transition through the treatment chamber, so that each pulse is applied to the fluid slug in a different configuration. Hence, it is essential to expand research for a continuous system and simulate its distribution of electric field and temperature with flow dynamics.

Computational modeling, coupled with fluid dynamics, electrical and thermal problems associated with the treatment chamber, permits characterization of the distribution of the process variables. Furthermore, modeling identifies the areas with an excessive electrical field, hot spots, and flow blockage that produces overheating and, potentially, dielectric breakdown. Hence, computational modeling needs to be done because of severe variations in the distribution of electric fields, temperature, and velocity profile (Masood, Razaeimotlagh, Cullen, & Trujillo, 2017).

Liquid food treatment has required multiphysics modeling and its application in the fluid dynamics coupled with the electric and thermal fields inside the treatment chamber (Knoerzer, Juliano, Roupas, & Versteeg, 2011). Gerlach et al. (2008) reviewed the numerical studies executed on the PEF process and suggested a solution of coupled fluid dynamical, electrical, and thermal problems associated with the treatment chamber. PEF processing at high flow rates requires an accurate model of fluid dynamics, and the introduction of a turbulent model is equally important. Several models for the description of turbulence exist (Huang et al., 2013). These models can be used for the development of this technology.

3. Power supply requirements for PEF system

One of the most critical challenges in PEF processing is the development of a desired pulsed power supply. The complexity and the high development cost of the pulsating system is the main hindrance for the commercial availability of PEF systems (Buckow, Ng, & Toepfl, 2013; Kandušer et al., 2017; Krishnaveni et al., 2017). The building blocks (design) of high-voltage pulse generation for liquid food treatment is similar to any other pulse generator but with different characteristics (Redondo, 2017, pp. 1–21). The difference between these designs is usually made by evaluating the overall cost of the process. While linear supplies can be designed at low cost, it requires to be operated beyond the critical threshold level to confirm effective treatment (Tokusoglu et al., 2014). In this section, we shall discuss and compare some significant techniques for high voltage pulse generators in PEF treatment.

3.1. Energy requirement

The average energy required in a PEF system is calculated as:

$$P_{ave} = V_{max} * I_{max} * \tau_p * f \tag{2}$$

'P_{ave}' is the average power supplied to the system, 'V_{max}' Maximum Pulse voltage (volts, from the modulator), 'I_{max}' peak current (amps, into the treatment chambers), 'τ_p' effective pulse-width (seconds) and 'f ' pulse frequency (Hz). Commercial applications desire to minimize the required amount of energy to achieve the desired results, which minimize the cost of the PEF process.

Sampedro et al. (2013) used a 35–40 kV cm^{-1} field and 2.5–4 μs pulse widths to treat orange juice-milk based beverage using different energy levels. They reported an inactivation level of 1.5 log reductions when 200–285 $kJ.L^{-1}$ of energy were applied and noticed small changes in inactivation when the energy applied was raised from 813 to 891 $kJ.L^{-1}$ (Sampedro, Rivas, Rodrigo, Martínez, & Rodrigo, 2007). Furthermore, they continued to increase the energy from 1069 to 1170 $kJ.L^{-1}$ and reported a 2-log reduction. Such an energy level is relatively high and could initiate thermal processes. It is known that an energy level of 200 $kJ.L^{-1}$ would be the most efficient level (Izabelanair, 2018).

PEF based food processing is an energy-saving technique relative to thermal processing. For liquid food treatment, the required energy inclusion, the application of an electric field of 40 kV cm^{-1}, and energy of 100–200 kJ kg^{-1} is effective (Table 1). In a study, substituting conventional preheaters with PEF technology in the pretreatment of potato, the energy requirement has decreased by 85% (Fauster et al., 2018). There was a reduction of 50% in the electric consumption associated with the reduction of the maceration time (Ferreira et al., 2019). PEF-based food processing offers an exclusive opportunity to decrease the energy expenses of bio-refineries through careful targeting of the cell membranes.

3.2. High voltage pulses

High voltage pulses generated by the power modulator affect the treatment efficiency. A particular value of the applied voltage across the treatment chamber is required that can provide electric field strength above a critical value (Buckow et al., 2013). Table 2 displays the mathematical calculation of the electric fields with applied voltage and the dimensions of the treatment chambers. The excessive value of applied voltage causes energy to be wasted as heat into the food sample, which not only diminishes the energy efficiency but also increases the temperature of the treated food (Guionet et al., 2015). Table 1 shows that liquid foods require PEF strength in the range of 2–30 kV cm^{-1} for the treatment of liquid and semi-liquid. Solid foods require electric fields of less than 5 kV cm^{-1} for extraction, and 3 kV cm^{-1} is needed for dehydration of food (Tokusoglu et al., 2014).

3.2.1. Pulse shape

The characteristic impedance of the discharging circuit (pulse forming network and treatment chamber with sample food) controls the shape of the applied pulse. The conductivity of the sample controls the resistance of the chamber. As a result, the shape of the pulse is affected by changing the sample food with different conductivity. Among the possible pulse waveforms for food processing, rectangular, exponential, oscillatory, and combination of narrow and wide pulse duration pulses are used usually in a monopolar and bipolar mode (Kumar, Patel, & Kumar, 2015; Qin et al., 2015).

Most of the researchers have used either rectangular or exponential decay (ED) waveforms for the treatment of foods (Elgenedy et al., 2017; Parniakov et al., 2016). Rectangular shape pulses with fast-rising and falling edges are the most efficient because the process yields low-temperature increases (Kempkes, 2017, pp. 1–21). All practical waveforms have limited the rise and fall times, where the full voltage is not present (Sack, Keipert, Herzog, Song, & Mueller, 2015). Therefore, an exact rectangular waveform is more complex and expensive to produce. The ED pulse offers a narrow peak of high-intensity electric field and a lengthy tail of the low-intensity electric field. Since a useful part of the ED waveform is very small, it is less efficient in PEF processing applications. However, it is simpler and cheaper to develop than the rest of the pulse waveforms (Elgenedy et al., 2017).

A unidirectional impulse of a nearly double-exponential (DE) waveform is represented by the difference of two equal magnitudes exponentially decaying waveforms that quickly rise to a peak value and gradually fall to zero value. This waveform is widely used in high-power electromagnetics. The efficiency of PEF to permeabilize biological cells is mainly dependent on the part of the applied pulses (time) during which the electric field strength exceeds a specific critical value (Luengo & Raso, 2017). Fig. 3 shows this effective part (shaded part; under the required voltage and within specific pulse width) of three different waveforms in food processing. It shows that ED is the least effective, and the rectangular waveform is the most efficient in PEF processing applications. "DE" pulse shape can be more effective than "ED" since it decreases the power losses of the electrical system, and a superior treatment can be achieved at a reduced cost (Arshad et al., 2019).

Over the last decade, research has been carried out on the requirement of bipolar modulators for PEF versus monopolar modulators (Li et al., 2016; Rao, Lei, Jiang, Li, & Kolb, 2018). Narrow high-intensity bipolar pulses are the best solution to reduce the corrosion of electrodes. Bipolar waveform will allow swapping the cathode/anode, which will prevent charge accumulation and thus slow down the degradation of quality due to electrolysis (Zhang, Li, Wang, Chen, & Du, 2018). There are inconsistent outcomes in studies that studied the performance of mono-versus bipolar PEF. However, the bipolar pulses do not produce a superior performance compared to monopolar pulses at pulse-width μs (Beveridge, MacGregor, Anderson, & Fouracre, 2005). From a designing point of view, a bipolar modulator is much more complex and expensive as it requires more power switches than the monopolar one. No compelling arguments for the use of bipolar modulator have appeared up till now that appears to justify its increased cost for industrial PEF systems.

3.2.2. Pulse width

Commonly, pulse width (τ_p) is the function of both the discharging circuitry and the resistivity of the sample being processed. For any application, the treatment time is the function of both the 'τ_p' and applied frequency of the pulses. For a fixed electric field strength, the treatment intensity increases by increasing pulse width and/or frequency will promote the formation of pores depending upon the structure of the sample cells (Mannozzi et al., 2019). There is an inverse relationship between field strength and pulse width, such as smaller

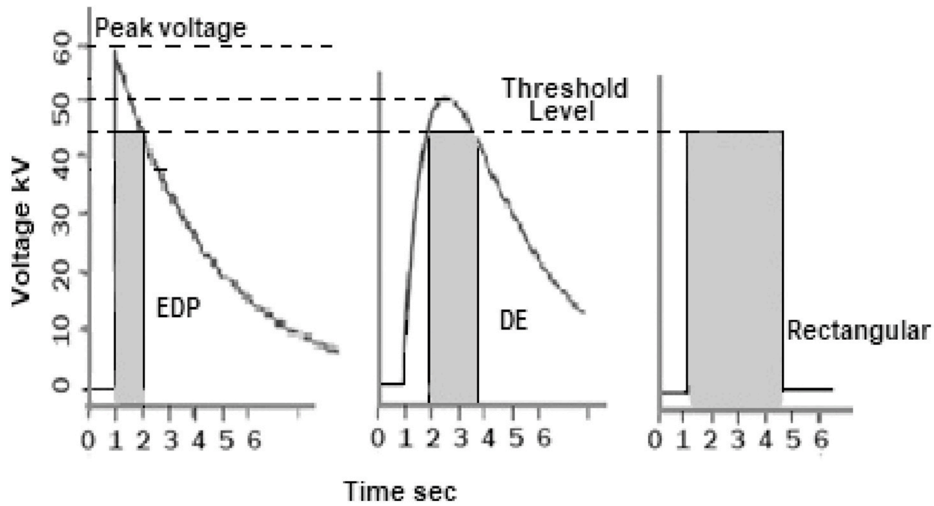


Fig. 3. Effective area (shaded) of different waveforms for PEF-based food processing; Exponential-Decaying (ED), Double-Exponential (DE), and Rectangular.

field intensity with broader pulse width can attain similar results as some higher field intensity with a narrower pulse width (Korolczuk et al., 2006). For effective PEF processing, the electric field intensity (kV. cm^{-1}) and average specific energy ($kJ.kg^{-1}$) should be enough to process the target cells even with a short pulse width (hundreds of nsec) (Elgenedy et al., 2017). During PEF treatment, wider duration applied pulses contribute more to the total energy input and more effective in irreversible electroporation (Guionet et al., 2015). However, localized thermal effect and electrolysis limit the pulse width to microseconds with the higher value of the electric field.

Table 1 shows the required range of pulsed widths with the associated value of the electric field. Some researchers have also utilized a combination of microseconds and nano-seconds pulses for liquid food treatment (Žgalin, Hodžić, Reberšek, & Kandušer, 2012). However, this approach does not lead to many fruitful outcomes but does increase the complexity of the circuit. Additionally, if the triggered pulse width is more than the time constant associated with the equivalent resistance of liquid in the chamber and the generator capacitance, the waveform is more likely to be a decaying pulse rather than a square pulse (Moonesan and Jayaram, 2013).

Thus, pulses in the range of few μs are suitable for PEF treatment of liquid foods, and hundreds of μs are required for enhancement of the extraction and drying processes (Table 1). Applying either pulse of milliseconds (40 ms with 5 kV cm^{-1}) or microseconds (75 μs with 20 kV cm^{-1}) improved the extraction of carotenoids from C. Vulgaris cells by 80% (Luengo & Raso, 2017).

3.2.3. Pulse frequency

Pulse frequency, as stated earlier, contributes to the treatment time along with pulse width. The generation of pulsed electric fields requires relatively slow charging of the system compared to the fast, high-energy discharge of the capacitors often requires significantly longer time spans (about 100–1000 times) between the pulses than the width of the pulse itself. Hence, a PEF processing with a frequency of a kilohertz is commonly required in the industrial treatment of liquid foods, and multiple of ten Hz is needed for the enhancement of the extraction/drying process.

As more food sample is processed, the average power also goes up. The processing of moving foods at high speed/flow requires more average power (energy per unit time) and increases the system cost. Without increasing the pulse-width, the only remaining choices are to raise the peak power in each pulse (which directly increases the cost of the pulse generator of processing system) or to increase pulse frequency (Gaudreau, Hawkey, Petry, & Kempkes, 2005). With the help of solid-state power switches, the use of a high frequency is recommended to provide a solution for this high energy demand. However, high frequency produces higher switching losses in the high voltage pulse generator (Tokusoglu et al., 2014). Due to the heating of the power switches, there is a tradeoff between maximum current and frequency.

3.3. Power switches

The power switch is probably the most expensive component of any pulse generator. It is an interface component between the energy storage devices and the load. It controls the characteristics parameters of the output pulse and determines the speed as well as the power ratings of a modulator. Closing switches are required with capacitive storage, whereas inductive storage components need an opening switch (Redondo, 2017, pp. 1–21). In PEF processing, gas/liquid-filled and semiconductors switches are appropriate choices of switches. The gas/liquid gaps are typically used for high standoff voltage and low inductance during closing. However, semiconductor switches are considered best for pulsed power switching due to the numerous advantages, as mentioned in Table 5 (Kempkes, 2017, pp. 1–21).

The power switches are categorized into closing (semi-controlled) or closing-opening (fully controlled) (Table 5). Closing switches must be capable of staying open, keeping the full input voltage until they are commanded to close. When they are closed, a current will continue to flow through the switch until the input power is dissipated (Qin et al., 2016). Normally, closing switches must wait until there is zero current (or a reverse voltage) to open again and prepare for the next pulse. In contrast, closing-opening switches are fully controlled and can be switched on and off.

When a power switch circuit is opened, the current flowing through the switch is interrupted, and high potential difference develops across the switch, a condition that is termed “stress of the power switch” (Kempkes, 2010; Toepfl et al., 2014). The switch must be capable of bearing the stress under full current and hold off the full voltage while open (Wu, Tseng, Wu, & Chen, 2006). These stresses cause power switches to melt/fuse. The switching stresses are compensated through soft-switching schemes are utilized. The soft switching is accomplished by allowing current to flow.

Table 5 shows that gaseous switches can hold a voltage up to 1000 kV with current up to 100 kA but can switch with a frequency of only 10 Hz. However, their operational life is very small, and it requires frequent replacement. In contrast, solid-state switches such as metal oxide semiconductor field-effect transistor (MOSFET) and insulated gate bipolar transistor (IGBT) have limited switching power with high pulse repetition frequencies in the food processing range.

Table 5
Power switches for PEF treatment.

Technology	Switches	Characteristics	Power rating	Advantages	Disadvantages	References
Material filled Switches	Spark gap	Unidirectional, semi-controlled closing switch filled with gas at high-pressure	1 MV; 100 kA	Low jitter; voltage-controlled trigger; high dv/dt; smaller turn-on & turn-off	Low repetition rate; limited lifetime; less reliable; internal losses, expensive, heavy; high pressure	(Kumar et al., 2019; Hudgins et al., 2017
	Thyratron	Unidirectional, semi-controlled closing switch filled with gas at low-pressure	100 kV; 10 kA	Low forward drop; voltage-controlled device; smaller turn-on and turn-off time	Low repetition rate; limited lifetime; less reliable; internal losses, expensive, heavy; high pressure	
	Ignitron	Unidirectional, semi-controlled closing switch filled with liquid at low-pressure	50 kV; 100 kA	Switching speed 100pps; high reliability and durability; high dv/dt; low forward drop; environmentally friendly	Extra care for cooling is required; operational issues, jitter issues	
Solid-state Switches	Thyristors	Unidirectional, semi-controlled closing solid-state switch	10 kV; 50 kA	Needs a pulse to change into conducting mode so easy to trigger; low losses; low cost	Unidirectional devices; lower operating frequency	Silva et al. (2018)
	IGBT	Fully controlled opening-closing silicon switch	8 kV; 1 kA	Fast turn-on & turn-off; voltage-controlled trigger; switching speed 10 kHz, cascading operation; durable to overvoltage; low on state power dissipation;	Low current tail due to carrier recombination; turn off slowly from fault condition; cannot block high reverse voltages	
	MOSFET		3 kV; 500 kA	Ultra-fast turn-on & turn-off; current-controlled trigger; switching speed 1 MHz, cascading operation; switching speed MHz, cascading operation; less power dissipation	Large on-resistance; susceptible to overload voltages	

3.4. Pulse generator topologies

The pulse power generators have been used in different applications, including PEF technology. The design of a pulse generator for any PEF treatment application is a complicated task. For a modulator to be used in industrial processing, a high consistency for continuous operation and an economical price are essential (Kempkes, 2017, pp. 1–21). Therefore, several studies have investigated the fabrication of high-efficiency pulsed generators that can be used in PEF technology (Chen et al., 2017; Novickij et al., 2016; Qin et al., 2015; Rao et al., 2018). The objective in every design was to efficiently realize the preferred PEF treatment system at the lowest cost and assure the operator's safety (Granato et al., 2018). Transmission lines (pulse forming a line), hard generators, hybrid modulators, Marx generators, and stacking switches are among the commonly available types of generators. Table 6 shows the advantages and disadvantages of different types of pulse generators developed and used in PEF treatment of liquid food.

The pulse generator needs to work inside the average power accessible from the charging power supply, so:

$P_{max} * f * \tau_p < P_{ave}$ of the DC power supply (W)

where 'P_{ave}' is the average power of the DC power supply (Watts), 'P_{max}' is the maximum power required from the pulse-generator (Watts), supplied to the system, 'f' pulse frequency (Hz) and 'τ_p' effective pulse-width (seconds).

Table 6 compares the various pulse modulators available for PEF treatment. It shows that gaseous switch-based topologies are still used in industrial processing to overcome the triggering limitations in stacked switches (Chen et al., 2017). Additionally, they are still competitive compared to semiconductor switches based technologies because of their low price and simplicity of design. Researchers have focused on utilizing low power semiconductor switches for industrial PEF applications (Elgenedy et al., 2017; Moonesan and Jayaram, 2013). Researchers are also struggling to develop new semiconductor switches with high power ratings and affordable prices. The following section describes the different categories of pulse modulators used in this treatment process.

3.4.1. Transmission line pulser

The transmission line or pulse-forming line is the most common topology for the generation of nano-seconds high-voltage square wave shape where a cable is used as an energy storage device (Beveridge et al., 2005). Blumlein generator uses two transmission lines to overcome the double voltage charging. Simplicity, short circuit tolerance, twice operating current, and low development price are the significant advantages of these designs. However, it is often inconvenient to match the characteristic impedance of this generator with the impedance of the treatment chamber. Moreover, it cannot provide pulses in the micro-second regime (Rao et al., 2018). Hence, it is essential to replace this bulky generator with a compact pulse generator having a higher frequency and wider pulse width. In this topology, switch action is closing or opening, but not both.

3.4.2. Transformer based topology

A pulse transformer with a gaseous switch is a good choice to obtain a high voltage output. Although it provides an output voltage that is well below the voltage rating of a switch, and thus provides good insulation. However, it suffers from several limitations such as low repetition rate, poor controllability of the output waveform, and low output current. The output pulse waveform is limited by the parasitic elements (inductances) of the transformer and losses of the magnetic switch core material. The core volt-second product imposes limitations to change diverse operating parameters, such as pulse width and repetition rate. Additionally, it is compulsory to retune the magnetic flux of the core to the original position after each pulse, and it requires an additional supporting circuit (Redondo and Silva, 2009). Thus, a pulse with a fast rise time is challenging to realize due to the transformer's leakage inductance. Moreover, some reset circuitry is needed to stop the saturation of the transformer. It is excessively massive, and designing of a pulse transformer is also a tedious task. Hence, usage of pulse transformer is not an appropriate solution for PEF applications as it is tedious to achieve very low primary loop inductance and very low leakage.

3.4.3. Gaseous switch-based topology

A series circuit of capacitor bank with a high voltage gaseous switch has been used extensively in PEF treatment both at commercial and experimental levels. These switches can handle a current up to 100 kA and voltages up to 50 kV and fulfill the requirements of the effective PEF treatment (Gad et al., 2014). These designs require a much larger power supply that is normally twice the rating of the output voltage. A short life, low repetition rate, complex trigger circuitry, and more rise and fall time are the main drawbacks of this topology (Krishnaveni et al., 2017).

Table 6
Comparison of pulse generators for PEF processing.

Modulator type	Advantages	Disadvantages	References
Transmission-line Generator	High voltage; simple and cost-effective; easily generate rectangular waveshape	Low current; overweight; complex switching element; impedance matching required	Beveridge et al. (2005)
Transformer Based Generator	High voltage; simple design; cost-effective, low power components are required; good isolation	Low current; the circuit is required to reset the core; shape is limited parasitic inductances; require PFN for rectangular waveshape; casecadability issue	(Li et al., 2016)
Gas-filled switch-based generator	High voltage/current; simple design	Low repetition rate; huge DC power supply is required; require PFN for rectangular waveshape; protection of the load; exactly as would a hard-switch	Gad et al. (2014)
Multilevel inverters-based generator	High voltage/current; generate rectangular waveshape; fast rise/fall time; good isolation; accurate square pulse	Costly solution; complex design; requires isolating transformers	Elserougi et al. (2017)
Solid-state Marx bank generator	High voltage/current; simple design; cascade-ability; fast rise/fall time; generate rectangular waveshape; low power components are required	Costly solution; complex design; use optical fiber for synchronizing the trigger	(Sack et al., 2015; Moonesan and Jayaram , 2013)
Cascaded Solid-state generator	High voltage/current; fast rise/fall time cascade-ability; generate rectangular waveshape; low power components are required	Required transient protection at each stage and optical fiber for synchronizing the trigger	(Chen et al., 2017; Gaudreau et al., 2005; Krishnaveni et al., 2017)

Thyratron switch is widely used for the pulse modulator designing for PEF treatment (Bastaki, Gaouda, El-Hag, & Jayaram, 2012; Gad et al., 2014). However, it cannot generate a square waveform and an additional pulse forming network (PFN) is required to develop a square wave, which is difficult to implement (Bastaki et al., 2012).

Gaseous switches are still looking for an attractive alternative to whimsical solid-state switch modules, especially when it comes to peak currents over 1 kA with pulse width less 1 μs, and peak voltages over 20 kV (Alirezalu et al., 2020). However, in most commercial applications, service time not less than 1 billion shots, and the price is a critical requirement. This can be achieved with a type of gaseous switches called, cold cathode thyratron, due to cost-effective and long lifetime solution.

3.4.4. *Solid-state H-bridge topology*

The improvements in semiconductor technology have made it feasible to rely on the PEF power supply based on solid-state switches. Solid-state pulse generators have many advantages, such as variable output voltage, pulse width, and frequency, long lifetime, stability, and compactness. MOSFETs and IGBTs have demonstrated benefits such as high-speed switching, efficiency, and controllability (Elgenedy et al., 2017). IGBT is more appropriate than MOSFET for pulse generator applicable in the PEF treatment because of their lower conduction losses and improved power handling capacity. To compensate for the low power ratings of the solid-state switches, combinations of these switches have been used in the pulsed power supply.

In PEF treatment, the modular concept in Cascaded H-bridge multilevel inverters (CHMI) configuration can generate well-defined pulses as its rise and fall times are fast, and the amplitude is stable (Elgenedy et al., 2017). Half-bridge and full-bridge (H-bridge) topologies are the most common way for the generation of bipolar pulses (Elserougi, Massoud, & Ahmed, 2017). However, many levels are required to have enough square wave output voltage generators. Isolated power sources are required in each stage, which in turn requires a large isolating transformer. Thus, it increases the cost of the device and is therefore not recommended for PEF treatment of fruit juices.

3.4.5. *Solid-state cascaded topology*

It is evident from Table 6 that cascaded (combination) solid-state switches is the best choice for PEF processing. The medium rated power switches can be stacked to tolerate maximum power instead of using single high rated one. It reduces the financial cost of the system design. However, a variation of external capacitance, turn-off time, and leakage current of the switches causes the voltage inequality between these stacked switches. Furthermore, a delay in trigger time from a drive circuitry, jitter in the gate trigger, and stray inductance are problematic in cascading topologies (Flisar et al., Meglic, Morelj, Golob, & Miklavcic, 2014; Redondo, 2017, pp. 1–21). However, these shortcomings can be overcome with the use of fiber optic cable for triggering the solid-state switches. The uneven cooling of an individual switch also leads to uneven stress. A non-punch through type IGBT is particularly ideal for series interconnection assemblies due to its positive temperature coefficient.

The research conducted by Diversified Technologies, Inc., in this area, is particularly valuable (Gaudreau et al., 2005). They have implemented a commercial PEF unit using IGBT switches stacked in series to produce a high voltage bipolar pulse generator (Chen et al., 2017; Sack and Mueller, 2017). The output of the generator can be as high as 60 kV, and 35 A. However, a series connection of switches will increase the stray capacitance and inductance of the circuit along with synchronization and precise voltage distribution (Butkus, Tolvaišienė, & Kurčevskis, 2019). All of these factors require a voltage balancing circuit for the series-connected IGBTs and add complexity to the circuit (Piazzesi & Meysenc, 2004). Another circuit has proposed stacking 64 IGBTs for the PEF treatment with a capacitor-diode snubber circuit to overcome the uneven distribution of voltage (Chen et al., 2017). The results showed that the developed system works at a delay time of 380 ns with 35.8-kV voltage and 44.8-A current capacity. However, a feedback loop in the control circuit makes it complex, and failure of one switch can stop the whole system.

3.4.6. *Solid-state marx bank topology*

Marx bank generator makes it conceivable to use a comparatively low voltage power supply and switches for achieving a high level of the output voltage by voltage multiplication (Silva, Redondo, & Dillard, 2018). However, the implementation of more stages increases some system complexity and losses (Yao et al., 2012). Additionally, slow charging of the Marx bank and low repetition rate are the limitations of this topology (Sack et al., 2015). Since charging a capacitor with a semiconductor switch is faster than a resistor, it facilitates to get uniform and repetitive rectangular pulses in micro and nano-seconds (Bermaki et al., 2015). The benefits of this design include cascade-ability and a smaller DC input voltage. However, the isolation transformer is obligatory between each stage. The transient protection in each stage is the point that must be included to make this design more reliable. Generally, for industrial PEF processing, solid-state switches are preferable in the topologies of stacking switch or Marx bank development.

3.5. Electrical transient compensation

Cascading of multiple solid-state power switches in different configurations are essentially required for the development of pulse modulator for PEF treatment. In this case, the application of transient compensation circuitry is obligatory to diminish the switching stress and synchronize the power switches. However, the voltage balancing circuit also contributes to circuit losses. Additionally, the short-circuit termination should be tested for possible flashover in the treatment chamber (Sack et al., 2015). Snubber circuits are widely used in pulsed power supplies to limit the stresses on the semiconductor power switches due to the stray inductance in the circuit. The snubbers are employed to overcome overvoltage, overcurrent, switching losses, and excessive rate of changes on the switch (Zhong, Chen, Zhang, & Kang, 2014, pp. 3658–3663).

Some common topologies of the snubber circuits are positively polarized, reverse polarized and non-polarized. The time constant of these circuits confines the dV/dt and dI/dt. Practically, snubber capacitors must be connected as close as possible to the power switch. Freewheeling diode parallel to each switch is another cheaper solution than RC snubber (Sack et al., 2015). Clipping the pulse can also be considered as a technique to confine the abnormalities in the output pulse due to the occurrence of transient processes. The crowbar circuit is used to limit overvoltage on the switch due to the inductive loads and reverse-biased currents.

3.6. Control & monitoring system

Control & monitoring system is a central part of this technology. It is used to control and measure the processing parameters such as voltage and current at the treatment chamber, temperature, speed of the food sample (Spink, Ortega, Chen, & Wu, 2017). Also, it helps to record the online process conditions to check and prevent uneven processing conditions. Apart from the overall temperature of the treated sample measured at the outlet of the treatment chamber, treatment inhomogeneity, and the occurrence of temperature peaks within the treatment chamber must be measured as thermal impact factors. The conventional thermocouples can only be applied remotely from the treatment zone because of high electric field strength in the treatment area. However, the use of optical transducer allows temperature measurement inside the treatment area. Therefore, proper positioning of sensors for temperature detection and online data analysis are essential elements for PEF processing system.

3.7. Conclusions and future recommendations

Investigations for the use of PEF technology for the treatment of foods at the research scale provided very promising results for the upscaling of the technology. This article examined recent developments in the electrical systems for validating PEF processing. In a continuous system, the distributions of electric fields and temperature with turbulent flow dynamics are needed to gain a better understanding of optimization for the process safety and efficiency. A designer must take into account the electrical resistance of the treatment chamber with a sample to calculate the required current for treatment. The solid-state Marx bank and stacking of IGBT switches are encouraging topologies for the designing of pulse modulator for PEF treatment. During the designing of a power modulator, the transient compensation circuit must be employed to protect the solid-state switch. Unlike ordinary cables, the Fiber Optics Cables are swift. These are considered promising for the connection between the control circuitry and the power switch to prevent any delay between the triggering of power switches. Since many of the researchers have widely developed double exponential pulse modulators for high-power electromagnetics applications, these modulators should also be tested for food treatment in place of exponential decaying pulses. PEF processing benefits are not limited to some specific category of applications and can also be used onto different industries, for example, the pharmaceutical industry where low thermal treatment can be valuable as well.

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