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Application of Nanotechnology in Waste Water Treatment

Yingshan Liang[1,*]

[1]Wycombe Abbey School, High Wycombe HP11 1PE, England

Abstract. In the past few years, there has been a growing concern about the pollution caused by fossil fuels, leading to a significant interest in photovoltaic power generation due to its clean and environmentally friendly features. However, suppressing leakage currents is a major problem for Non-isolated PV inverters. This paper focuses on the leakage current suppression methods, summarises three main leakage current suppression paths and systematically analyses and classifies the DC-bypass topology, the H5 topology and the Neutral Point Clamped (NPC) three-level topology. In order to address the issue mentioned above, several approaches can be taken. Firstly, a suitable sinusoidal pulse width modulation strategy is implemented. Additionally, alterations are made to the common mode impedance Z. Furthermore, efforts are made to ensure a proper match of circuit parameters. The analyses in this paper are all carried out based on bridge-type inverters to provide a reference for the study of leakage current suppression in Non-isolated Inverter. Future studies will be more efficient when similar issues arise.

1 Introduction

Water is crucial for supporting life on Earth, with it being involved in almost every aspect of human activity, ranging from maintaining basic cellular functions to the development of cutting-edge technology. Whilst the Earth's surface is greatly covered by water, fresh water only constitutes about 3% of it, of which a large proportion is locked up in glaciers or underground, making it even more difficult to access safe water [1]. In addition, increasing rates of industrialisation have served to worsen water quality through the contamination of water sources with industrial waste. Therefore, water quality is also a concerning issue [2]. Currently, one out of three people lack access to safe water across the globe and this can be directly linked to waterborne diseases such as diarrhoea and cholera [3]. Therefore, recycling used water and treating waste water is crucial in ensuring wider accessibility to clean water. Currently, the most commonly seen methods of water treatment involve flocculation, sand filtration, biodegradation, and absorption using activated carbon [2]. However, there are several drawbacks associated with these processes such as large amounts of sludge waste produced and their inability to target smaller contaminant particles. Hence, novel technologies are needed to address these problems [2].

Among those technologies currently under development, nanotechnology is considered one that has achieved relative success. Nanomaterials are those that have at least one dimension which measures under 100 nanometres and the main processes include adsorption, filtration and photocatalysis [4]. Nanomaterials have been generally used due to their large specific surface area, effectiveness in targeting nano-scaled contaminants, antibacterial properties and low solid waste production [2]. This paper will summarise various forms of nanotechnologies integrated into waste water treatment and analyse their suitability as well as the potential for development.

2 Nanotechnology in waste water treatment

2.1 Nanoadsorbents

Adsorption plays a key role in waste water treatment. Currently, the most widely applied adsorbent in waste water treatment is activated carbon due to its high removal efficiency of multiple contaminants [2]. However, there are also several disadvantages associated with activated carbon such as high regeneration costs and lack of selectivity towards some particles, resulting in difficulties in obtaining and recycling certain substances in waste water, thus reducing its economic viability [2]. Nanoadsorbents apply both chemical and physical adsorption mechanisms and are advantageous due to their small size, which gives rise to their large specific surface area, resulting in more efficient adsorption [4]. Most common types of nanoadsorbents can be categorised into the following: metallic and metal oxide-based, carbon-based, zeolites, and polymeric nanomaterials [4].

Metallic and metal oxide-based nanoparticles are used as their versatile properties enable effective pollutant removal in water. Many of these nanoparticles possess antibacterial properties which makes them beneficial in removing pathogenic microorganisms from waste water. Owing to their small size, nanoparticles can

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[*] Corresponding author:17LiangA@WycombeAbbey.com

enter cell membranes and disrupt the functions of the cell. Certain nanoparticles can also be oxidised by oxygen, which releases metal ions and creates reactive oxygen species [5]. This oxidation reaction can be initiated through various means such as by light or dissolving under a neutral pH [5]. One example of this is Ag NPs which are among some of the most widely used nanoparticles. Whilst both Ag NPs and AgNO3 are effective in reducing algal photosynthetic yield. Navarro et al. found that although initially AgNO3 displayed higher toxicity, after the removal of a large proportion of the particles by cysteine, Ag NPs were more effective in preventing photosynthesis of algae at lower concentrations, which was the result of the constant generation of Ag+ ions [6]. Under aerobic conditions, Ag NPs were oxidised to produce Ag+ ions that can enter the cell and destroy major cell components, whilst in the absence of oxygen, Ag+ ions were not released [6]. On the other hand, metal oxide nanoparticles such as ZnO NPs are also capable of producing reactive oxygen species such as the superoxide anions by absorbing photons when exposed to light [5].

Carbon-based nanomaterials have wide applications in waste water treatment. They possess advantages such as high specific surface area, high stability, low costs, high adsorption capacity and the fact that their surface properties can be easily modified and enhanced by oxygen-containing functional groups [4,7]. Carbon nanotubes (CNTs) are common nanomaterials employed in waste water treatment and are used to remove synthetic dyes, heavy metals and organic waste [7]. The adsorption abilities of a material are dependent on the material's specific surface area, availability of surface-active sites, and contaminant affinity [7]. CNTs consist of rolled-up graphene sheets and can be singled-walled (SWCNTs) and multi-walled (MWCNTs). The graphene sheets result in a hydrophobic surface of the CNTs due to the density of π electrons, and hydrophobic interaction with contaminant molecules takes place at these walls [8]. The presence of these π electrons also promotes the interaction of CNTs with the π region of aromatic rings, giving rise to the effective adsorption of organic wastes such as 1,2-dichlorobenzene [8]. This suggests that CNTs are effective in removing organic waste from waste water, especially those that have high π electron density. Brooks et al. found that whilst CNTs do not necessarily possess an advantage over activated carbon in terms of uptake of materials, their adsorption sites have greater accessibility [8]. This implies that further research into ameliorating the adsorption ability of the adsorption sites of CNTs will have a significant impact on their adsorption capacity. As mentioned above, the properties of CNTs can be modified with the addition of functional groups. Charged functional groups will result in strong electrostatic forces between the adsorption surface and adsorbate, rather than weak Van der Waal's forces. These stronger interactions suggest more effective adsorption, hence showing the importance of surface functionalization and in turn the benefits of using carbon-based nanomaterials as they can be easily modified with functional groups. Mubaraka et al. found that the addition of HNO3 and H2SO4 to the CNTs resulting in carboxylic groups on the surface led to a higher percentage removal of synthetic copper ions (94.5% compared to 61%), reinforcing the benefits of surface modification [9]. As mentioned above, AgNPs possess antibacterial properties and can effectively target bacteria cells. However, they also have certain shortcomings such as their bio-compatibility and toxicity towards hosts [10]. This means that carbon-based nanoparticles may be more favourable as also possess antibacterial properties but are not associated with these issues [10]. In general, carbon-based nanoparticles possess many advantages meaning that they can effectively remove contaminants from waste water, especially given their notable high adsorption rates [10]. However, the significant costs of CNTs and other carbon-based nanoparticles restrict their large-scale uses, giving an advantage to other adsorbent alternatives. In addition, whilst the toxicity of carbon-based nanomaterials varies greatly depending on the exact material, more experimental data is needed to find the most suitable applications for these costly innovations [4].

Nanozeolites are nanomaterials composed of aluminosilicate minerals. Their high adsorption capacity is due to their high specific surface area and porous structure. Zeolites can act as effective carriers for different nanoparticles. Due to the porous structure of zeolites, they are able to offer high elimination rates of bacteria as the nanoparticles are more accessible [11]. Egger et al. studied the antimicrobial properties of three different substances that all acted as a carrier for nanosilver ions on various forms of bacteria cells and fungi [11]. From their results, the minimum inhibitory concentration of silver nanocomposite when tested on Escherichia coli (E.coli) was 62.5 µg/ml, compared to that of silver zeolite which was 3.9 µg/ml, whilst the minimal bactericidal concentration of E.coli after being treated with 0.2 ml of the silver nanocomposite and incubated for 24 hours was 125 µg/ml, compared to that of silver zeolite under the same conditions which was 31.2 µg/ml [11]. This trend was affirmed by all the microorganisms tested in their study, proving that under the time and condition the experiment was carried out, a lot less silver zeolite was required to prevent microbial growth, pointing towards their efficiency and possible cost-effectiveness [11]. They hence related this to the rate at which silver ions are released in solution by these different compounds, suggesting that silver zeolites have higher efficiency in the mass removal of high concentrations of bacterial cells under short periods whilst proposing that silver nanocomposites can offer long-lasting targeting effects on bacteria due to their slower but steady release rates of nanosilver ions [11]. This could possibly lead to different applications of these silver-containing nanoparticles, where silver zeolites are employed in systems that are frequently exposed to high concentrations of bacteria, whilst silver nanocomposites could be used in areas that are under constant but low exposures of bacteria. As well as being a site of silver ion exchange, nano-zeolite themselves are applied as they have a desirable adsorption capacity of contaminants such as industrial dyes. Hammood et al.

studied the effects of various distinct parameters in zeolite nano-adsorbent dye removal rates [12]. When they increased the initial concentration of the dye from 25 mg/L to 200 mg/L, they saw a steady increase in the weight of the dye adsorbed, suggesting the high adsorption capacities of zeolite [12]. The weight of the dye adsorbed also increased when the quantity of nano-zeolite applied increased from 0.0025 g to 0.02 g, which was a result of more adsorption sites available [12]. They also studied the effects of varying pH on nano-zeolite's adsorption capacity. The initial concentration of the solution was kept constant whilst pH levels of 2,6,7 and 8 were tested for 120 minutes [12]. Their results showed that a pH level of 6 yielded the highest weight of dye adsorbed (around 0.2 mg/g) whilst a pH level of 2 adsorbed less than 0.1 mg/g of dye [12]. They attributed this to a greater amount of H+ ions competing alongside cationic dyes for adsorption sites on the nano-zeolite at a lower pH [12]. On the other hand, their results also showed a decrease in the weight of dye adsorbed above a pH level of 6, with the most significant decrease between pH 7 and 8, hence they concluded that zeolite nano-adsorbents have a neutral optimum pH for adsorption [12].

Polymeric nanoadsorbents are repetitively branched molecules that have ideal mechanical and chemical properties for pollutant removal. They have large surface areas and their mechanical rigidity and pore distribution make them well-suited for waste water treatment [13]. Perhaps the biggest advantage polymeric nanoadsorbents possess over traditional activated carbon is that their adsorption processes are reversible, meaning that certain molecules can be desorbed and retained for recycling, which makes it economically advantageous [13]. Another advantage polymeric adsorbents have over traditional adsorbents is their accessibility and cost-effectiveness. Materials such as activated carbon are relatively expensive, whilst many polymeric nanoadsorbents are biocompatible and abundant in nature [2]. This means that they can be more easily sourced hence lower production costs, as well as smaller environmental impacts. Siakamari et al. investigated the removal rates of lead ions by chitin nanofibres and chitosan nanoparticles [14]. Chitin nanofibres were fabricated by passing a suspension of chitin microfibres through a machine mill whilst chitosan nanoparticles were produced through an ionic gelatinous interaction under room temperature, both processes were relatively achievable, bringing an advantage to these polymeric nanoadsorbents [14]. When they increased the initial concentration of Pg (II) ions, they found that adsorption rates became constant above a concentration of 100 ppm of Pb (II) ions, which they assumed was the maximum adsorption capacity of the polymeric nano-adsorbents [14]. They then tested with much lower concentrations of Pb (II) ions (2 ppm to 10 ppm) and found that the removal rates of both nanoadsorbents were over 95% for all concentrations [14]. Chitin nanofibres achieved a near 100% removal rate between 4ppm to 6 ppm whilst chitosan nanoparticles achieved a near 100% removal rate between 4ppm to 8ppm, with chitosan nanoparticles slightly outperforming chitin nanofibres under each concentration, but both nanoadsorbents were effective in removing Pb (II) ions [14]. This suggests the advantage of these more easily synthesised, biocompatible polymeric nanoadsorbents in waste water treatment at lower concentrations and their suitability compared to more costly alternatives under certain conditions [14]. Both Chitin and chitosan are non-toxic, biodegradable, biocompatible polymers that can be sourced in large quantities in nature, confirming the idea that naturally occurring polymeric nanoadsorbents have the potential to compete with activated carbon as a contaminant adsorbent [14]. In addition, many polymeric nanoadsorbents have been used as a hybrid with inorganic nanoparticles such as metal ions or metal oxides [13]. Whilst many of these nanoparticles offer advantageous properties, their size and strength may result in them being in suitable for use standalone use in waste water treatment [13]. Thus, combining polymeric adsorbents with inorganic nanoparticles will serve to enhance the applications of both. Khaydarov et al. studied nanocarbon conjugated polymer nanocomposites (NCPC)'s effectiveness in the removal rates of heavy metal ions from water [15]. NCPC was synthesised through the addition of polyethyleneimine solution and nano carbon colloids and they found that at a pH level of 6, the NCPC displayed the highest bonding capacity of 4.0-5.7 mol/g and adsorption rates were high with an almost 100% removal after the first minute, showcasing the effectiveness of NCPC [15]. In addition, they found that the NCPC generated had a short lifetime of less than 8 minutes, meaning that they would not remain in the filtered water for long hence concerns with the environmental and health impacts of NCPC are unnecessary [15]. However, this could also pose setbacks to the large-scale application of NCPC in waste water treatment as they would need frequent renewal.

2.2 Nanomembranes

Filtration is a major process in waste water treatment as it is responsible for the removal of large quantities of contaminants. Whilst sand filtration is a well-established method employed in waste water treatment, it is faced with challenges similar to that of activated carbon, such as selectivity, efficiency and clogging, which result in a less satisfactory quality of water under current demands [2]. Hence, various types of nanomembranes have been developed as an alternative in order to overcome these problems. Similar to many other nanotechnologies applied, nanomembranes are characterised by their large specific surface area, relative stability, and their ease of modification. As their name may suggest, nanomembranes target particles sized around 0.1-10 nanometres and typically remove dissolved solids and liquids through a pressure-driven diffusion process through dense, selective layers due to their non porous structure, high removal rates can be attributed to their very fine structure [16]. Nanomembranes are typically used to remove soluble solids in a liquid and hence would be applied in the later stages of water purification [16].

Perhaps the two greatest factors that affect the functionality of a membrane are flux and selectivity. The former plays a key role in maintaining efficiency and the latter is paramount in ensuring water quality. Flux is closely related to permeability and has an inversely proportional relationship with the thickness of the membrane, hence nano-scaled membranes are advantageous [17]. One problem that has prompted research into improved designs of nanomembranes is the trade-off relationship between permeability and selectivity [18]. Whilst current market demands may indicate greater requirements for membranes with higher selectivity, both parameters play key roles in nanofiltration, hence it would not be a good idea to solely focus on improving selectivity [18]. Another problem associated with membranes is fouling which is irreversible and would have severe impacts on the efficiency of the membrane [19].

Nanocomposites membranes are perhaps some of the most commonly seen nanomembranes employed in waste water treatment. These membranes have varying amounts of nanoparticles added through different methods which serve to enhance materials properties including charge density, hydrophilicity, stability and antibacterial properties [20]. Conventional nanocomposites have nanoparticles finely dispersed throughout the polymer matrix [20]. A variety of inorganic nanoparticles can be added to the polymeric membrane which serves to ameliorate its properties. The addition of different nanoparticles will serve to enhance different aspects of the membrane. For example, He et al. synthesised a polyvinylidene fluoride (PVDF) ultrafiltration membrane with the addition of nano ZnO particles using phase inversion and used it to treat 0.5 g/L Bovine Serum Albumin (BSA) aqueous solution [21]. In comparison with the membrane without the ZnO nanoparticles, they found that the addition of these particles reduced the mean pore radius from 0.153 μm to 0.115 μm, which played a significant role in increasing rejection rates from 87.26% to 98.4%, as well as decreasing flux [21]. This example demonstrates the versatility of nanocomposite membranes and that they can be easily modified to meet different requirements. The reason why these nanoparticles are able to change the structure could be attributed to the exothermic hydration process of these nanoparticles, which would then affect reactions during its formation process and alter the structure of the membrane [20]. In addition, Kim and Deng showed that fouling decreases with increasing surface hydrophilicity [22]. This is advantageous as fouling results in less membrane flux, impacting the efficiency of the membrane. Apart from dispersing nanoparticles into the polymer matrix, modifying the membrane surface using nanoparticles has also proven to be effective [20]. Attachment methods of these nano particles include self-assembly, coating/disposition, electrostatic attraction, chemical grafting, adsorption reduction and many others [20]. An advantage associated with these surface-located nanocomposite membranes is that they do not affect the functions of the original membrane, hence they could be applied on existing membranes, suggesting cost efficiencies [20]. Madaeni et al. synthesised reverse osmosis (RO) membranes coated with TiO2 particles and tested their properties under UV radiation [19]. TiO2 particles are UV catalysts and hence would be able to break down materials deposited on the membrane surface, reducing fouling [19]. They found that not only did these nanoparticles have photocatalytic effects, but they also greatly increased the surface hydrophilicity, which is evident through the reduce of water contact angle from 43° to 9° [19]. Both of these properties will result in the reduction of fouling, which will serve to promote the separation efficiency of the membrane. Whilst this experiment was carried out under conditions for reverse osmosis rather than nanofiltration, suggesting higher pressures applied, the results can be extrapolated for nanofiltration due to the similarity in the mechanism of the two processes.

As mentioned before, the trade-off relationship between selectivity and permeability is a challenge faced by all synthetic membranes, and hence the development of novel membranes is currently underway in order to mitigate these problems. One example of this is Aquaporin based membranes. Aquaporin-based membranes are composed of membrane proteins that join together to form a hydrophilic water channel under certain conditions [18]. These channels will only transport water and hence reject all other solutes, hence a compromise is not required, meaning that they would be effective in terms of ensuring quality, efficiency and fouling resistance [18]. Aquaporin-based membranes are inspired by the lipid bilayers found in living cells and have the capacity to transport up to a billion water molecules each second, suggesting their efficiency [18]. However, limitations to the wider applications of Aquaporin based membranes are greatly due to the cost of production as the synthesis of the bilayers employs advanced technologies such as atomic force microscopy [18]. Li et al. fabricated Aquaporin membranes by incorporating them into a Thin Film Composite (TFC) membrane as proteoliposomes and tested their performance using sodium chloride solutions [23]. They showed that the addition of Aquaporins into the membrane not only resulted in high stability, but could also be related to high water transportation rates across the membrane [23]. However, when they tested these membranes with actual sea water they found that whilst Aquaporin based membranes offered 80% greater water flux than normal TFC membranes, the overall solute rejection rate was 1% lower than that of TFCs, which was particularly evident in monovalent ions [23]. This suggests that whilst the structure of Aquaporins may be extremely advantageous in terms of water flux, more refinement is needed in the models of these membranes in order to maximise their beneficial properties [23]. Zhao et al. compared the RO performance of membranes containing wild AquaporinZ (AqpZ), those that contain mutant AqpZ R189A, and a TFC control with no Aquaporins [24]. They found that the membranes containing wild AqpZ displayed much higher water permeability than that of the other two used. Hence they concluded that Aquaporins played a key role in increasing the water permeability of the membrane as the one containing mutant AqpZ did not show similar results [24]. Whilst they found that the rejection rate of wild AqpZ membranes was only the highest at a 5.0 pressure bar and was overtaken by the TFC control at higher pressures, it should be noted that these experiments were conducted under the conditions for reverse osmosis, which applies greater pressures than nanofiltration, suggesting their less of an impact in terms of nanotechnology applications [24].

2.3 Photocatalysis

Photocatalysis refers to an oxidation process that is initiated by radiation within a specific wavelength which serves to remove pollutants and bacteria. Many nanoparticles can act as photocatalysts such as TiO2, tungsten trioxide, and various fullerene derivatives [4]. Due to their high ability to degrade pollutants, in particular organic waste, they are widely applied in waste water treatment alongside nanomembranes and adsorbents [19]. TiO2 is a semiconductor that could perhaps be considered the most commonly used photocatalyst. Its mechanism can be summarised as follows. When it is exposed to light within a particular wavelength, electrons are excited from the capacity band into the conduction band, resulting in electron-hole pairs on its surface [19]. The excited electrons react with available oxygen to produce superoxide anions, whilst the electron-hole pairs react with water to generate OH radicals [19]. Both of these are toxic reactive oxygen species (ROS) and have the ability to cause oxidative stress on cells, hence eliminating the pollutants. However, TiO2 is a UV catalyst meaning that it can only work under UV radiation, so it is often doped with different metals in order to extend its functions into the visible spectrum, which is advantageous as visible light can increase the generation rate of ROS [25]. Chelli et al. studied the effect of bimetal doping of TiO2 using copper and zinc nanoparticles under visible light which yielded a 98% removal rate of Congo red dye under a pH of 5 [25]. This was not only way higher than without the dopant (14.1 %), but also much greater than that of doping with just copper (68.7%) and just zinc (59.3%), proving the effectiveness of bimetal doping on photocatalysis of contaminants [25]. However, the effects of bioaccumulation of TiO2 nanoparticles on aquatic life have also been analysed and results show that they may negatively impact marine life in terms of reproduction and respiratory rates, structures of gill and intestine as well as several other factors [4]. Similar to carbon-based nanoadsorbents, this can indicate an indirect impact of the toxicity of these nanoparticles on human life.

3 Conclusion

This paper reviews nanotechnology applied in wastewater treatment. Nanomaterials have advantages such as versatility, large specific surface area, antibacterial properties as well as minimal waste residual owing to the nature of their size. These factors all contribute to their effectiveness in pollutant breakdown and removal. One clear advantage of nanomaterials is that they are able to target much smaller contaminant particles than flocculation and sedimentation, producing water of much higher quality. Nanotechnology has also been used to mitigate certain challenges faced by traditional water treatment methods such as fouling and the trade-off relationship between selectivity and permeability. Currently, there exist two major setbacks to larger-scale applications of nanotechnology in treating waste water: the cost of production and maintenance under their working conditions and the need for more extensive experimental data to fully maximise their advantages in real-life applications. These would only come with time and large sums of investments into further studies of different forms of nanotechnology. However, nature is an area where future innovations can take inspiration from, as it could offer a promising alternative solution to certain current challenges as well as being more environmentally sustainable.

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