Efficient Charge Transfer Process in an Intelligent Electrical Storage System

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Abstract— In this paper, we propose an effective method for electrical energy storage using charge transfer concept. It is especially assigned to the intermittent suppliers in the renewable energy domain. The corresponding device operates according to two principal functional modes. The first is the well known standard charge control converter. It is used when the level of the available energy from the supplier is greater than a given threshold. Otherwise, the device is switched to the second functional mode where it acts as a charge pump which extracts the maximum energy from the supplier and introduces it in the storage unit. The proposed device is designed to be polymorphic and to guarantee an optimal charge transfer, since it is able to get a self reconfiguration to move a maximal amount of electrical charges, from the suppliers to the accumulators, with minimal energy loss. The polymorphic behavior of the system allows us to use it as a charge supplier or a charge balancer inside the storage units. In order to use interchangeably the two functional modes to guarantee the optimal result in real time, it is necessary to know continuously the state of charge of each accumulator and the level of the available energy at the renewable supplier. The distinguished renewable energy sources for which this system is assigned are solar photovoltaic and wind generators.

Keywords- Electrical energy Storage, Supercapacitor, ultracapacitor, charge transfer, polymorphic capacitor, renewable energy, Pump of charge.

I. INTRODUCTION

The best way to deal with the shortage of fossil fuels is to exploit the free renewable energy received by our planet (solar, wind...). To do this, we must create strong and fast devices to transform and store this energy. During the recent decade, the supercapacitors (SC) are known as the well suited components of the electronic power, that are able to store energy directly basing on an electrostatic field, which is completely different from the principle of the electrochemical based process on the standard battery. The supercapacitors (Or ultracapacitors) can be charged and discharged thousands of times (> 10,000) faster than conventional batteries by providing extremely high power in a short time period [1]. Due to this performance, they became quickly the most used support for electrical renewable energy storage. The only feature that must be developed to make the supercapacitor an ultimate storage device is its energy density [2, 17]. Nanotechnology development and the recent understanding of the charge storage mechanisms in a supercapacitor allow scientists to improve the characteristics of this important component. Currently, new supercapacitors reaching 60 Wh per kg begin to be marketed, but research laboratories have already managed to create ultracapacitors with an energy density of 600 Wh per kg. Thus, a high energy density device technology will be the most efficient way to store energy produced by renewable sources and particularly, home photovoltaic systems that are booming [15,16]. In this way, we aim, by this work, to develop an optimal recovering energy system, from renewable sources, even under unfavorable conditions (low radiation, low wind ...) and store it in a polymorphic device, based on supercapacitors, in order to inject this energy into a storage warehouse consisting essentially of supercapacitors. Compared to an electrochemical battery, a supercapacitors characterized by a fast power transfer, low internal resistance, wide temperature range, the possibility of a deep discharge and the ability to load and unload quickly for long time (> 100 000 times) [2]. These features make supercapacitors the most appropriate components for use in applications with a large number of charge / discharge cycles [3]. Although, still lower energy density than batteries [4], these components offer new possibilities in the management and energy storage, especially when combined with intermittent energy sources such as wind turbines or photovoltaic generators.

In order to satisfy the need of power of a given load, it is necessary to make associations of many capacitor cells in series and in parallel to reach the energy storage performance of electrochemical batteries [7] [8] [9]. Due to the capacitance gap between the elements of the stack cells, the voltage difference between the cells becomes significant after a large number of charge and discharge cycles. This will damage the cells of low voltage [10]. Also, this voltage difference affects the output power of the super capacitors. Thus, to overcome the mentioned constrained challenges, an appropriate management technique of the voltage balancing over the cells or batteries is frequently used [5] [6].

This paper is organized as follows: Section II, is focused on the charge and energy exchange concept between capacitors, where we discuss the needed tools to characterize the energy transfer, and develop in more details the energy transfer process, when connecting two parallel capacitors, to highlight the suitable criteria to choose the values of the capacitors to improve the efficiency of the charge transfer. In the same section we present the simplified process, we adopted for recovering energy from a renewable source by using a charge pump circuit.

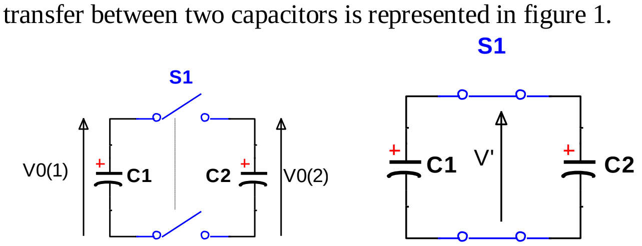
section III, deals with the operating principle of our device to show how it recovers the energy as low as it is, and how it uses the principle of a polymorphic capacitor of various configurations depending on dynamic (serial / parallel) associations. The algorithm of the optimal energy storage is also presented to show how we can associate the charge balancer and the charge pump to achieve an efficient storage system. The last section presents some concluding remarks and some perspectives of the work.

II. CHARGE AND ENERGY TRANSFER OPTIMIZATION

As mentioned above, the aim of this work is to recover energy from renewable sources and store it in a polymorphic device to be transferred into a warehouse of supercapacitors. Before designing such a system, we must study the process of energy transfer between two capacitors, and the concept pump of charge. After identifying the optimal conditions for charge transfer and charge pumping, we propose a method using alternatively the two concepts to accomplish optimal renewable energy recovering. During this study, we will deal just with the steady state of the resulting circuits in terms of voltage, current and energy. This study allows us, according to the available input energy of the intermittent suppliers, to determine in real time the size of the charge transfer container, named "polymorphic device".

A. *Charge transfer analysis*

The basic device allowing the analysis of the charge transfer between two capacitors is represented in figure 1.



a) *b)*

Figure 1. Charge transfert circuit

In this circuit, before switching “ON” S1 as in figure 1.a, we assume that the initial stored charges in the two capacitors are: Q1(0) and Q2(0) , the total charge in the circuit is :

$$Q0 = Q1(0) + Q2(0) \quad (1)$$

In the same way, the initial energy of the capacitors are: W1 (0) and W2(0) and the initial energy of our system is :

$$W0 = W1(0) + W2(0) \quad (2)$$

At the starting time t=0: S1 is switched “ON” (figure 1.b), the capacitors are parallel connected. Assuming that: $V_1^{(0)} > V_2^{(0)}$ then C_1 will charge C_2. Their voltages V_1 and V_2 versus time are as follows:

$$V_1(t) = \frac{C_1.V_1^{(0)} + C_2.V_2^{(0)}}{C_1 + C_2} + \frac{C_2}{C_1 + C_2}.\left(V_1^{(0)} - V_2^{(0)}\right)e^{-t/\tau} \quad (3)$$

And

$$V_2(t) = \frac{C_1.V_1^{(0)} + C_2.V_2^{(0)}}{C_1 + C_2} - \frac{C_1}{C_1 + C_2}.\left(V_1^{(0)} - V_2^{(0)}\right)e^{-t/\tau} \quad (4)$$

where: τ = Req.Ceq (Req $=R_1+R_2$) the internal serial resistors of C_1 and C_2, $Ceq=C_1C_2/(C_1+C_2)$.

At the steady state, the capacitors reach the same voltage V’. The charges in C_1 and C_2 are: Q1(1) and Q2(1) respectively; so, the total charge in the circuit is :

$$Q1 = Q1(1) + Q2(1) \quad (5)$$

Subsequently, the total energy of the system is:

$$W1 = W1(1) + W2(1) \quad (6)$$

According to the charge conservation law, we have:

Q0=Q1, so, V’= Q0/(C_1+ C_2).

The table 1 summarizes the different states of the circuit, before and after switching ON the switch S1.

In table 1. Comparing the energy amounts before and after switching “ON”, S1, we can see that there is a loss of energy during the charge transfer between C_1 and C_2. This energy loss rate is expressed by:

$$\eta = \frac{W_0 - W_1}{W_0} = 1 - \frac{W_1}{W_0} \quad (7)$$

In order to minimize η, we will look for the optimal conditions and the relationship between capacitors C_1 and C_2, and between voltages $V_1(0)$ and $V_2(0)$, to guarantee the minimal energy loss during any charge transfer phase.

Assume that: $C_1=\alpha.C_2$, V_1 and V_2 the initial voltage of C_1 and C_2 respectively, before switching “ON” S1.

After switching “ON” S1, the final voltage at the steady state is:

$$V' = \frac{\alpha.V_1^{(0)} + V_2^{(0)}}{1 + \alpha} \quad (\mathbf{8})$$

So, the total energy of the system is:

$$W_1 = \frac{1}{2}C_2\frac{\left(\alpha.V_1^{(0)} + V_2^{(0)}\right)^2}{1 + \alpha} \quad (9)$$

And the energy loss rate is:

$$\eta = 1 - \frac{\left(\alpha.V_1^{(0)} + V_2^{(0)}\right)^2}{(1 + \alpha)\left(\alpha.\left(V_1^{(0)}\right)^2 + \left(V_2^{(0)}\right)^2\right)} \quad (10)$$

	Capacitor C_1		Capacitor C_2		System { C_1, C_2 }	
Time: T	Initial condition	Steady state	Initial condition	Steady state	Initial condition	Steady state
Charge: Q	$C_1.V_1^{(0)}$	$C_1.V'$	$C_2.V_2^{(0)}$	$C_2.V'$	$C_1.V_1^{(0)} + C_2.V_2^{(0)}$	$(C_1 + C_2).V'$
Voltage: V	$V_1^{(0)}$	$\frac{Q_0}{C_1 + C_2}$	$V_2^{(0)}$	$\frac{Q_0}{C_1 + C_2}$	$V_1^{(0)}, V_2^{(0)}$	$\frac{Q_0}{C_1 + C_2}$
Energy: W	$\frac{C_1.(V_1^{(0)})^2}{2}$	$\frac{C_1.V'^2}{2}$	$\frac{C_2.(V_2^{(0)})^2}{2}$	$\frac{C_2.V'^2}{2}$	$\frac{C_1.(V_1^{(0)})^2 + C_2.(V_2^{(0)})^2}{2}$	$\frac{(C_1 + C_2).V'^2}{2}$

Table.1. Characterization of a charge transfer circuit.

Notice that for the case: $V_2(0)$ =0V (i.e. C_2 is totally empty before switching "ON" S1), we have :

$$\eta = \frac{1}{(1 + \alpha)} \tag{11}$$

If α=1 (i.e. C_1=C_2) then η=50%. This means that the energy loss rate is maximal, so the case of deep discharge is to avoid, otherwise the physical properties of the capacitors may be altered.

We can also generalize this study by assuming that:

C_1= $\alpha.C_2$ and V_2= $\beta.V_1$

Then, we have:

$$\eta = 1 - \left[\frac{(\alpha + \beta)^2}{(1 + \alpha)(\alpha + \beta^2)}\right] \tag{12}$$

Hence, the loss rate η depends just on α and β.

Fig 2.represents the evolution of η according to α and β

(α ϵ]0,1] and β ϵ [0.5, 1[ )

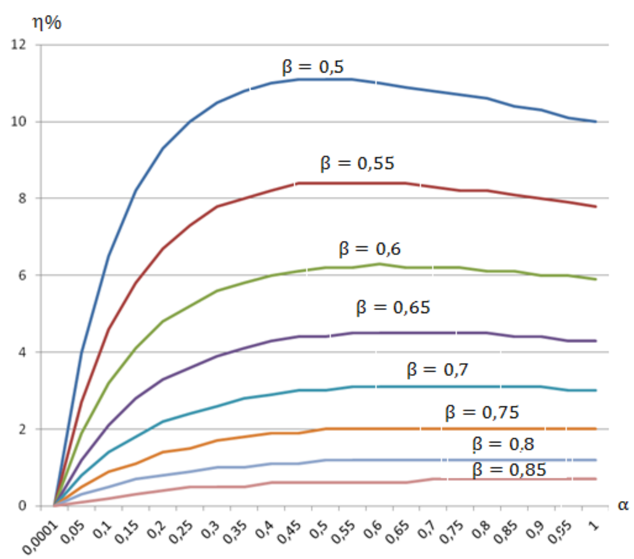


Figure 2. Variation of the energy loss ratio η=f(α, β)

In order to find the extreme value of η, we have to determine the derivative function according to α and β :

1st case : we consider that α is constant and β variable

$\frac{d\eta}{d\beta} = 0$ leads to : $\beta^2 + (\alpha - 1).\beta - \alpha = 0$ then :

β = 1 or β = - α .

This gives unpractical solutions. Indeed, β=1 corresponds to the case of two capacitors having the same voltage. So, there is no charge transfer, while for β = - α the capacitors must be connected in inverting polarity. This corresponds to a non practical configuration of our study.

2nd case: β is constant; then $\frac{d\eta}{d\alpha} = 0$ leads to :

$(\alpha^2 - \beta^2)(1 - \beta)^2 = 0$ then β= α or β=1.

Since β must be different to 1 to have a voltage gap, the valid case is β = α, this leads to :

$$\eta_{max} = 1 - \left[\frac{4.\alpha}{(1 + \alpha)^2}\right] \tag{13}$$

The following table 2. shows the different values of η_{max} depending of α from 0 to 1 using a step of 0,05. From this table, we can see that the energy loss is less than 2% when α ≥0,75, but if we accept the loss ratio of 11% we can choose the value α =0,5 (i.e. C_1=0.5 C_2).

As in [10] where the authors choose α =0.75 (i.e C_1=0.75 C_2), we can conclude that the suitable condition for maximal transfer of charge with low energy loss (η_{max} <2%) is to take C_1 and C_2 so that: $0,75.C_2 \leq C_1 \leq C_2$.

Table 2. Maximal energy loss ratio function $\eta_{max}= f(\alpha)$

α	0,5	0,55	0,6	0,65	0,7	0,75	0,8	0,85	0,9	0,95	1
η_{max}	11,11 %	8,43%	6,25%	4,50%	3,11%	2,04%	1,24%	0,66%	0,28%	0,07%	0,00%

Table 2, represent the accepted range for maximal transfer with minimal energy loss that corresponds to $0,5< \alpha<1$

In order to use perfectly the proposed charge transfer system, we need some essential parameters and state variables of the supplier capacitor and those of all the target capacitors of the storage unit. We need the values and the state of charge of these components with their voltages in real time. These parameters may be estimated or sensed to be more accurate. In the proposed example, if C_1 is assumed to be the recovery supplier capacitor that will collect the charges from the Renewable energy sources, and C_t is the targeted capacitor from the set of n storage units, it is necessary that, before connecting C_1 to C_t, our system must determine the target capacitor which fit the optimal conditions to make transfer of charge with minimal energy loss rate. To do so, the system must compute the parameters α_t and η_t for each peer (C_1,C_t) (t=1 to n) , then select the suited capacitor to which C_1 will be connected. The selected capacitor is the one that the optimal condition is closest to.

B. Charge pumping analysis

1) Presentation

A charge pump converts a voltage to another using capacitors that are charged and discharged into each other by means of controlled switches. There are several topologies and configuration of a charge pump [11, 12]. The principle scheme adopted for our charge recovery device is that of figure 3, where E is an ideal voltage supplier. In the real application context, E is replaced by a polymorphic capacitor circuit that corresponds to an intermediate storage container which is devoted to recover electrical charges from intermittent renewable energy sources. A and B are the controlled switches.

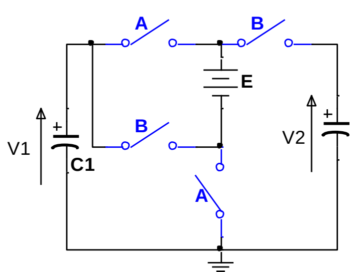


Figure 3. Example of a pump of charge circuit

let us discuss briefly the principle of a pump of charge. The proposed circuit of figure 3. operates as a two phases cycle:

Phase 1: The "A" switches are closed (switched “ON”) and "B" switches are “OFF”. The voltage of capacitor C_1 reaches E at the steady state.
Phase 2: The "A" switches are open (switched “OFF”) and "B" switches are closed (switched “ON”). The capacitor C_1 previously loaded to E is coupled in series with the supplier E to constitute a “2E” supplier which is connected to C_2 . This latter will start its charging from 2.E voltage, and the charge of C_1 will decrease, so that the added voltage to C_2 is derived from C_1 according to the (charge / discharge) equations (3) and (4).
This “two phases” cycle is repeated continuously until the capacitor C_1 became unable to transfer the charge. At this stage, the final voltage of C_2 will reach 2.E. Notice that this process may take several cycles for C_2 to reach the desired charge level value.
To describe the managing rule of the C_2 voltage as in [11, 12], we are interested in the steady state, starting from the following initial state where A and B are switched “OFF”:

- $V_1^{(0)}$ and $Q_1^{(0)} =C_1.V_1^{(0)}$: initial voltage and charge of C_1 respectively;
- $V_2^{(0)}$ and $Q_2^{(0)}= C_2.V_2^{(0)}$: initial voltage and charge of C_2 respectively.

Step 1 : Loading (B switched “OFF” and A switched “ON”)
At the steady state : C_1 is charged to E so , $V_1^{(1)}=E$ and $Q_1^{(1)}=C_1.V_1^{(1)}= C_1.E$. But C_2 keeps the charge of the previous state (initial state). $Q_2^{(1)}= Q_2^{(0)}= C_2.V_2^{(0)}$.
- Step 2 : Charge transfer (A switched “OFF” and B switched “ON”)
we have : $Q_1^{(2)}=C_1.V_1^{(2)}$, $Q_2^{(2)}=C_2.V_2^{(2)}$ and $V_1^{(2)}=V_2^{(2)}-E$
According to the charge conservation law, we have :
$Q_1^{(1)} + Q_2^{(1)} = Q_1^{(2)} + Q_2^{(2)}$

So : $C_1.E + C_2.V_2^{(1)} = C_1.[V_2^{(2)} - E] + C_2.V_2^{(2)}$

$$= (C_1 + C_2).V_2^{(2)} - C_1.E \quad (14)$$

Then ,

$$V_2^{(2)} = \frac{C_2}{C_1 + C_2}.V_2^{(1)} + 2.\frac{C_1}{C_1 + C_2}.E \quad (15)$$

let us take :

$a = \frac{C2}{C1+C2}$ where 0 < a < 1

$r = \frac{C1}{C1+C2}$ where 0 < r < 1

$b = 2.E.\frac{C1}{C1+C2} = 2.r.E$

So, equation (15) can be rewrite as follow:

$$V_2^{(2)}=a.V_2^{(1)} + b =(1-r).V_2^{(1)} + 2.r.E \quad (16)$$

in the general case, (16) is as a recursive equation as :

$$V_2^{(k)} = a.V_2^{(k-1)} + b. \qquad (17)$$

which will be rewritten as :

$$V_2^{(k+1)} = a^k.V_2^{(1)} + b.\frac{a^k-1}{a-1} \qquad (18)$$

On the other hand, the expression (18) can be considered as a recursive equation of a sampled system for which the convergence is guaranteed when a<1.

At the steady state (k goes to infinity), we can write: $V_2^{(k)}=V_2^{(k-1)}=V_f$

Subsequently; $V_f = b/(1-a) = 2rE/r = 2.E$, this means that the asymptotic limit of V_2 is 2.E.

The following table represents the V_2 voltage for different successive charging iterations (k), for three values of a: a=0,33 ($C_1=0{,}5C_2$), a= 0,5 ($C_1=C_2$), and a= 0,66 ($C_1=0{,}5C_2$), for E=20V and a worst case of deep discharge of C2 ($V_2^{(0)}$ = 0V).

Table 4. V_2 voltage for different pump of charge cycles (K) and different circuit capacitors.

k	$V_2^{(k)}$ (a=0,33)	$V_2^{(k)}$ (a=0,5)	$V_2^{(k)}$ (a=0,66)
0	0	0	0
1	26,667	20,000	13,333
2	35,556	30,000	22,222
3	38,519	35,000	28,148
4	39,506	37,500	32,099
5	39,835	38,750	34,733
6	39,945	39,375	36,488
7	39,982	39,688	37,659
8	39,994	39,844	38,439
9	39,998	39,922	38,960
10	39,999	39,961	39,306
11	40,000	39,980	39,538
12	40,000	39,990	39,692
13	40,000	39,995	39,794
14	40,000	39,998	39,863
15	40,000	39,999	39,909
16	40,000	39,999	39,939

From table 4 and figure 4, we can see that, smallest is the coefficient “a” (i.e. $C_2<<C_1$), the fastest is the circuit to reach its steady state.

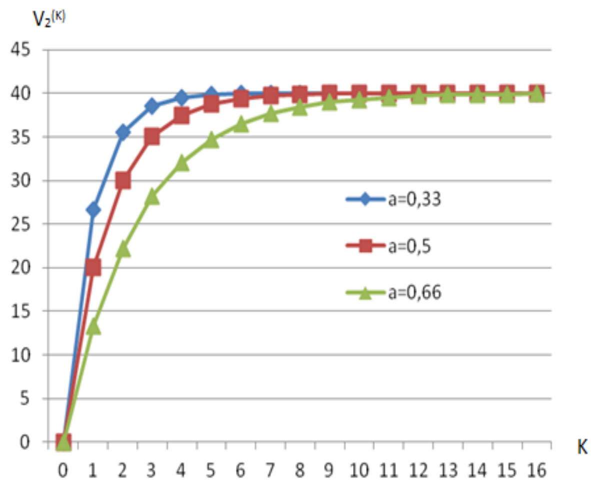


Figure 4. Evolution of the final voltage of C_2 according to a and cycle number K , $V_2^{(k)}$= f (K)

2) *Introduction of the pump in the charge transfer chain*

In this process, we will replace the ideal supplier E in the circuit of figure 3 (A_OFF and B_ON), by a polymorphic capacitor C_x whose capacitance value is self-configured according to the output energy supplied by the renewable source.

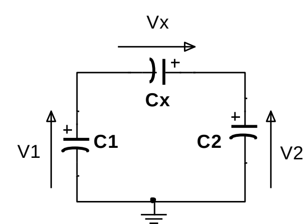


Figure 5. The pump charge circuit using Polymorphic capacitor C_x

Without loss of generality, in most cases of the charge transfer systems, we consider $C_1=C_2$. Also, C_{1x} is the equivalent capacitance of the serial circuit (C_1,C_x): $C_{1x} = \frac{C_1 C_x}{C_1+C_x}$

In order to guarantee the maximum charge transfer, it was shown in section II.A. that we have to take :

$C_{1x}=\alpha.C_2$ and $\beta.(V_1 + V_x)=V_2$ where $\alpha=\beta=0{,}75$ (loss of energy ratio η_{max} =2.04% see Table 1) and [10]

Generally, in the practical cases, we consider : $V_x<V_1<V_2$ and $V_1 + V_x > V_2$

So, $C_{1x} = \frac{C_1 C_x}{C_1+C_x} = \alpha.C_2$ then

$$C_x = \frac{\alpha.C_1 C_2}{C_1-\alpha.C_2} \qquad (19)$$

If $C_1=C_2=C$ then $C_x = \frac{\alpha.C}{(1-\alpha)}$ and $V_1 + V_x = V_2/\alpha$

Before switching “ON” S1, let us take : $V_2=V_1+e$.

So, $V_1 + V_x = (V_1+e)/\alpha$ then:

$$V_x = V_1 \frac{1-\alpha}{\alpha} + \frac{e}{\alpha} \qquad (20)$$

At this stage, we have to answer this fundamental question: What are the values of C_x and V_x to allow a maximum energy transfer, from C_{1x} to C_2, for a given α ?

To answer this question, it is interesting to use the results of section II.A. After the charge transfer step, we can see that the remained energy in C_x depends on its final voltage. Hence, we must check whether C_x is unable to transfer charges neither to C_1 nor to C_2. Then, it is necessary to find its suitable configuration allowing it to get additional charges to be transferred to the capacitors C_1 or C_2. This leads us to consider C_x as a polymorphic capacitor.

III. Energy storage by polymorphic capacitor

In this section, we consider an electric charge accumulation device based on the principle of a polymorphic capacitor which can take various patterns depending on the dynamic and automatic serial / parallel associations [13]. This device consists of a set C of *n* capacitors, $C = \{C_1, C_2, C_3, ..., C_n\}$, which can be represented, from different series and parallel associations, by its equivalent capacitor C_{eq}. The developed system has the ability to change its configuration according to some control rules on its associated switching device. It is a process that is intended to operate in the electric charges recovery systems, even if the supplier's voltage is lower than the threshold of the conventional converters. In order to store the maximum electric charges, the device must take itself in a suitable configuration to be adapted effectively to the magnitude of the supplier voltage and facilitate storage control. The device is adapted to any electrical energy source of intermittent voltage and power. It is designed to extract the maximum power from these sources and deliver it to the storage units. Storage units can be different of types: batteries, capacitors, supercapacitors, etc.

The control systems used to the battery charging are generally the standard converters based on the principle of charge transfer from a source voltage Vs to the storage units voltage E_{accu} where Vs> E_{accu}. During the charging process, the battery voltage increases until the maximal voltage limit E_{accu}max of the accumulator is reached, or until a balance situation between the two voltages occurs (i.e. Vs = E_{accu}) .

In the case of the standard charge controllers, when Vs < E_{accu}, the converters are unable to transfer charges from the supplier to the accumulator. Thus, we can consider that the energy produced by the supplier Vs is inoperative insofar it cannot be stored.

In the literature, there are some booster devices as in [14] that are able to raise the voltage Vs in order to satisfy the condition Vs > E_{accu}. In this case, it is necessary for the supplier to have enough power to be able to boost the energy transfer to the accumulator. The limitations of these devices are reached when the boosting conditions are not met, this is the case where the supplier power is less than the boosting threshold: Ps < P_{thmin}. To overcome the limitations of these conventional chargers and boosters, we propose a device that can work in lower conditions. It is a process able to receive energy as low as it may be and direct it to be stored in the charge accumulators. This device has two operating modes : collection and transfer ones. In each mode, it is self configured to take various and specific patterns to allow maximum power transfer.

The proposed polymorphic charging device is composed of a set of P capacitor branches connected in parallel, each branch comprising S capacitors serial connected. Thus, the total number of capacitors in this device is: n=P.S.

This device provides a voltage $V_o(t)$ which supplies a converter. Assume that its minimum operating threshold is $k.V_0$ where k <1 and V_0 the total voltage provided by the capacitor matrix (P, S).

During the charge transfer phase, the voltage of the capacitors continues to drop gradually as the charges are transferred. However this voltage cannot fall beyond a given threshold ($k.V_0$) associated to the converter. To continue extracting energy, by respecting $V_0(t) > k.V_0$, the system must launch an automatic switching parallel-series from P to P' branches where each new branch will consist of S' serial capacitors as in figure 6. So that : P.S=P'.S' (P>P', S<S').

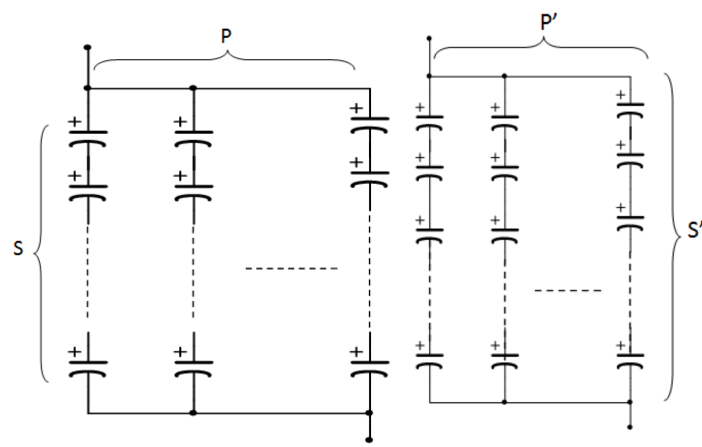


Figure 6. a polymorphic switched capacitor structure.
a) Capacitor matrix (P,S). b) Capacitor matrix (P',S').

Consider: $C_{eq\text{-}init}$, the initial equivalent capacitor of the (P,S) stack composed of P parallel branches of S serial capacitors each.

$C_{eq\text{-}f,}$ the final equivalent capacitor of the (P',S') stack having P' parallel branches of S' serial capacitors after switching.

The stored energy at the initial state is : $W_i = 0{,}5.C_{eq\text{-}init}\, V_o^2$, while the remained energy in the final state after several self configurations is :

$$W_f = 0{,}5.C_{eq\text{-}f}\,.(k.V_0)^2 .$$

The total extracted energy from the device is:

$$W_i\text{-}W_f = 0{,}5.(C_{eq\text{-}init} - k^2.C_{eq\text{-}f}).V_O^{\,2}$$

The percentage ratio of the total extracted energy is expressed by:

$$\eta = \frac{w_i - w_f}{w_i} = 1 - \frac{w_f}{w_i} = 1 - \frac{k^2.C_{eq-f}}{C_{eq-init}} \qquad (21)$$

Figure 7. shows an example of the basic switching circuit cell used to elaborate the polymorphic capacitor matrix of figure 6.

In this example, the process is started from the configuration P=2 the state where S1 and S3 are closed (switched "ON") and S2 is open (switched "OFF"), the two capacitors are connected in parallel. The voltage $V_0(t)$ will start to decrease from Vo to k.Vo, at this time, S1 and S3 will be switched (OFF) and S2 (ON), the two capacitors became in series (configuration P'=1) and the total output voltage will be 2.k.Vo which will start to decrease from 2.k.Vo to k.Vo. Without loss of generality, as a simple numeral example: If k = 50%, and $C_1 = C_2 = C$ then $C_{eq\text{-}init} = 2C$ and $C_{eq\text{-}f} = C / 2$ so; η= 93.75% . This indicates that 93.75% of this polymorphic capacitor energy can be supplied to the target capacitors in the storage warehouse.

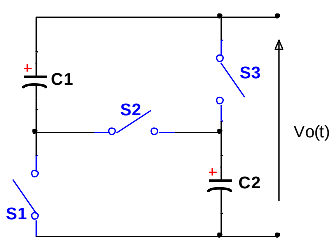


Figure 7. Elementary cell for serial /parallel capacitors association

The proposed device has two operating modes. The first one is the charge collection and storage inside its polymorphic container, the threshold voltage of energy transit is very low compared to the known standard charge controller devices. This is a fundamental characteristics of the container since where it can be self configured to receive charges from low voltage sources.

The second operating mode is the charge transfer to the destination accumulator E_{accu}. To ensure efficient disposal or transfer of charges, the device chooses the suitable configuration that allows it to easily satisfy the condition $Vs > E_{accu}$ and minimal loss of energy transfer as described in section II.A.

In the case where the source Vs is low, the transfer of charge by our system is done by alternating the two mentioned operating modes (collection, transfer) several times until the total charging of the target accumulator. At each operating mode, the device must check the closest optimal condition of charge transfer. Also, the process may be stopped when the condition of no energy from the supplier occurs (e.g. wind is stopped, or no sun for PV).

When $Vs > E_{accu}$, the case where the wind or PV source supplies a voltage higher than the one of a target cell, the system acts as a conventional direct charging.

Finally, the principal operations of this device are summarized as follows:

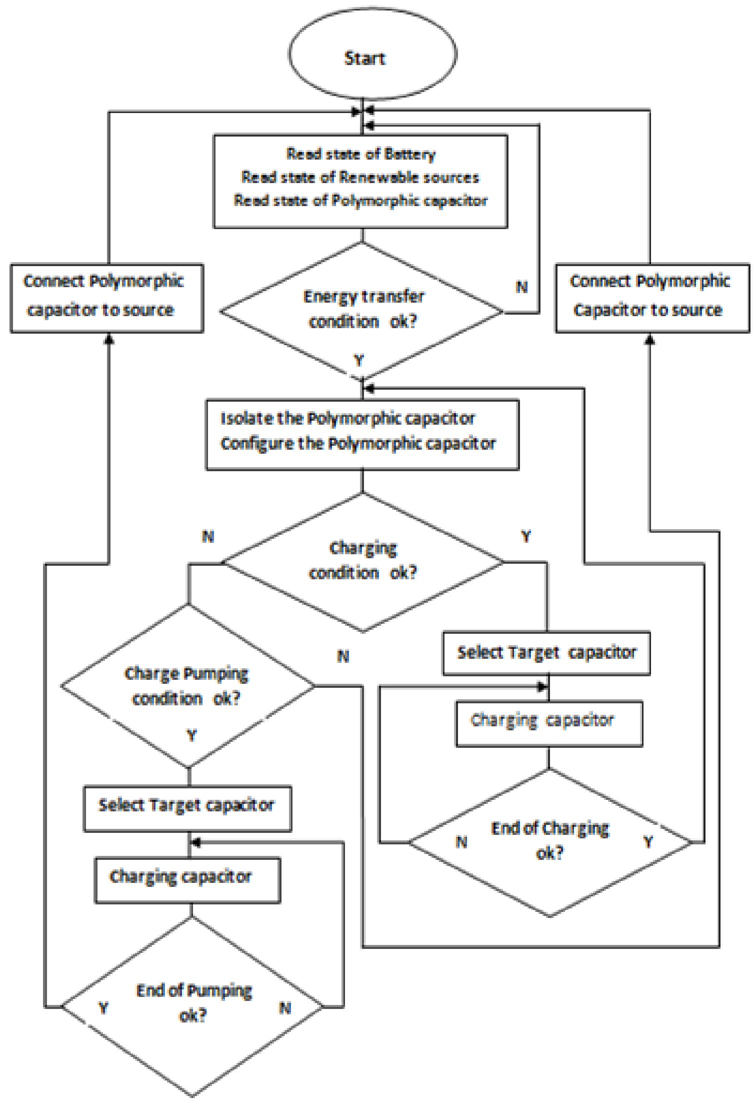


Figure 8. Polymorphic capacitor storage algorithm

Once ready to be connected to any supplier (principally the intermittent renewable electrical energy source) and the electric charge accumulation system (battery, capacitor or any kind of battery). The system must operate in accordance to the following steps:

Step 1: collect Information about the transfer of charge conditions.

• Read the status of the voltage source: PV, Wind or other supplier and measuring its output voltage Vs

• Read the status of the storage system $E_{acc;}$ State of charge of each accumulator.

• Read the status of the polymorphic capacitor: switching code of the matrix capacitor and State of charge of each capacitor.

Step 2: charging type analysis

a **-** Standard charging:

If Vs > E_{acc}, this means that the source is able to directly load the target accumulator. So our system works as a standard converter. It continuous working and checking the condition of step 1.

b **-** Polymorphic charging:

If Vs < E_{accu}, this means that the renewable energy supplier is unable to deliver charges to the battery via the standard device. In this case, our system is launched to work in two phases, the first one is the charge collection, it corresponds to the configuration of the device to receive electrical charges from the source Vs, these charges are collected to be transferred to the target accumulators. When the capacitors reach a given state of charge, the system looks for the best condition to transfer stored energy with minimum loss of energy. The following chart of figure 8. gives more details about the different parts of the proposed optimization algorithm.

VI. CONCLUSION

In this paper we have presented an efficient device for optimal energy storage using charge transfer concept. The proposed method is based on a polymorphic capacitor taking several, serial/parallel, configurations according to the available energy on the renewable sources, when it is in the recovery mode, and according to the storage accumulators' states when it is in the charge transfer mode. In real time, the system is able to follow the evolution of the renewable energy state. The managing algorithm of the device tries to achieve an optimal control of the energy recovery from the renewable suppliers. It operates in the same way to transfer charges to the storage units with minimal loss of energy. The charge transfer is realized using charge balancing and charge pumping processes to optimize the storage process. Also, some interesting concepts have been discussed to show their usefulness to achieve the main goal of the energy efficiency. Over this presentation we have discussed just the results of the steady state of the system. As perspectives of this work, we will deal with the dynamic behavior of the device where all the parameters will be taken versus time to make a fine choice of the different configurations to guarantee maximal energy transfer with minimal loss of energy during interaction between different components of the system.

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