MEMS Based DC to DC Converter using SUGAR Simulator

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ABSTRACT--- *DC-DC power converters have variety of applications, including power supplies for personal computers, office equipment, spacecraft power systems, and telecommunications equipment, as well as dc motor drives. The input to a dc-dc converter is an unregulated dc voltage Vg. The converter produces a regulated output voltage V, having a magnitude that differs from Vg. A dc-dc converter reduces the voltage to the regulated 5V or 3.3V required by the processor ICs. High efficiency is invariably required, since cooling of inefficient power converters is difficult and expensive. Crucial to the proper operation of the device is the condition of constant charge on the capacitor when its capacitance is reduced. This is ensured by a diode between input voltage and capacitor, the diode ensures that the charge on the load capacitance C(x) is maximum. In this work, MEMS based prototype DC-DC converter structure is simulated using SUGAR MEMS simulator.*

Keywords---- MEMS, DC to DC Converter, SUGAR Simulator

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1. INTRODUCTION

A DC-to-DC converter is an electronic circuit which converts a source of direct current (DC) from one voltage level to another. It is a class of power converter. It is a class of switched-mode power supply (SMPS) containing at least two semiconductors (a diode and a transistor) and at least one energy storage element, a capacitor, inductor, or the two in combination. Filters made of capacitors (sometimes in combination with inductors) are normally added to the output of the converter to reduce output voltage ripple. A switching regulator is a circuit that uses a power switch, an inductor, and a diode to transfer energy from input to output. The basic components of the switching circuit can be rearranged to form a step-down (buck) converter, a step-up (boost) converter, or an inverter. Feedback and control circuitry can be carefully nested around these circuits to regulate the energy transfer and maintain a constant output within normal operating conditions. A single-pole double-throw (SPDT) switch is connected to the dc input voltage V_g as shown in Figure 1. The switch output voltage $v_s(t)$ is equal to V_g when the switch is in position 1 and is equal to zero when the switch is in position 2. The switch position varies periodically, such that $v_s(t)$ is a rectangular waveform having period T_s and duty cycle D. The dc-dc converter in Figure 1 consists of a switch network that reduces the dc component of voltage and a low-pass filter that removes the high-frequency switching harmonics.
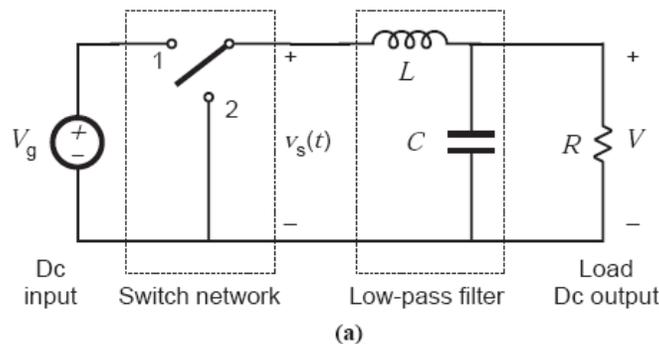
Fig. 1 DC-DC Converter with a switch network

1.1 Block Diagram of DC-DC Converter

The basic block diagram of DC-DC converter is shown in Figure 2, where the main supply given to the input rectifier and filter and the output is given to the inverter chopper. From the output of inverter chopper, it is given as input to the output transformer. The transformer output is again rectified and filters and is given as the DC output. Finally, the partial output rectifier is given to chopper controller which control inverter chopper.
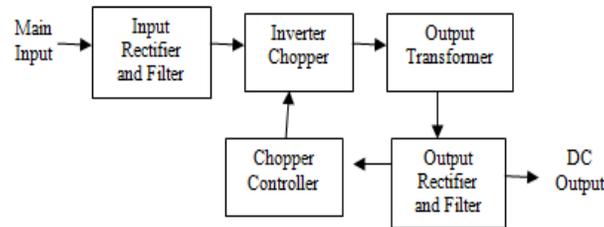
Fig. 2 Block Diagram of DC to DC

2. PREVIOUS WORK

E.M. Yeatman [2007] proposed applications of MEMS in power sources and circuits. It also presented power supply for electronics which has been explored for MEMS devices and techniques. Mitcheson P.D., et al., [2004] presented that power is extracted by damping the internal motion of the proof mass with an electromechanical transducer and transducer can be electrostatic, electromagnetic or piezoelectric. Holmes A.S., et al., [2005] proposed axial-flux permanent magnet machines for micropower generation. MEMS rotating generators using airflow driven turbines have been fully realized and demonstrate mW power levels. Sakaue, E. [2005] proposed the power supplies without moving the micromachining techniques of MEMS. Highly miniaturized fuel cells are being developed and micromachining offers advantages such as the use of micro fluidic channels in the separator plates. Noworolski and Sanders [1992] proposed an electrostatic micro-resonant power conversion device. Ayyaz Mahmood, et al., [2009] presented a silicon MEMS dc/dc converter to be used in autonomous mechanical energy scavengers, based on electrostatic transduction. Yen Mo Chen, et al. [2013] proposed a three-port dc-dc converter integrating photovoltaic (PV) and battery power for high step-up applications is proposed in this work.

Yen and Jeffery [2006] presented effective conversion of mechanical energy to electrical energy which can be used to feed wireless low-power electronic devices, by increasing the lifetime of a battery in a vibrating environment. C.H. Haas and M. Kraft [2004] presented the principle of a novel voltage step-up converter based on a micromachined variable parallel-plate capacitor in combination with an electrostatic actuator. Hua Yu, et al., [2014] presented MEMS piezoelectric power generator array for vibration energy harvesting. A complete design flow of the vibration-based energy harvester using the finite element method (FEM) is proposed. Wang and Nguyen [1999] presented the efficiency of micro-resonators can be increased by using a high dc bias voltage and electrical noise levels in capacitive accelerometers to reduced in a similar fashion. Han and Cho [2003] proposed self-balanced navigation-grade capacitive micro-accelerometers using branched finger electrodes and their performance for varying sense voltage and pressure. M. Suhonen, et al., [1998] presented Application of the pull-in voltage of a moving plate capacitor as a DC or AC voltage. J. Kyynäräinen , et al., [2000] presented an RMS-to-DC converter based on a SOI (silicon-on-insulator) process.

3. MEMS BASED DEVICES FOR DC CONVRERTER

The field of MEMS applications is very diverse in terms of the functions provided by the MEMS devices. Another growing application area within electronic systems is that of power supply. The most explored application of MEMS in this field is the generation of power from motion and vibration to which an integrated electro-mechanical technology is suitable. However, MEMS switches also have benefits for circuit protection and the use of micro-mechanical structures for energy storage results in potential uses in power conversion and conditioning.

3.1 Advantages of MEMS based DC to DC Converter

The MEMS based DC to DC converter advantages are,

(i)   MEMS devices compared to conventional solutions include small size, low power consumption, low price in mass production, stability and low frequency noise.

(ii)   The analog multiplication or fast sampling combined is needed to measure the true RMS value of arbitrary waveforms. Electrostatic MEMS components offer a new solution to true RMS-to-DC conversion.

(iii)   MEMS components have been developed for use as stable frequency references and when compared to the conventional quartz crystals the MEMS resonators are advantages.

4. MEMS BASED POWER GENERATION AND SWITCHING

MEMS devices provide coupling of electrical signals into the mechanical domain, where energy storage in moving masses and strained springs is possible. The dc–dc converter is based on a resonant MEMS structure. Typically, integrated dc–dc converters use switched oscillating circuits, with resonant LC tanks providing the energy transfer. However, integrating the magnetic materials is not straightforward and the inductive components cause significant losses, particularly at the high switching frequencies needed for high power densities. A mechanically resonant MEMS structure provides a possible approach to eliminating the magnetic components, while maintaining compatibility with monolithic integration. The schematic of a MEMS capacitor is shown in Figure 3, where upper schematic represents two variables capacitors, electrically isolated, but mechanically coupled as Figure 3(a). These are connected to the input and output sides respectively and is driven at their mechanical resonant frequency. The lower rectangles represent the anchored lower plates of the capacitors, while the upper plates are connected to their anchors via springs. An insulating mechanical link couples the two sides.
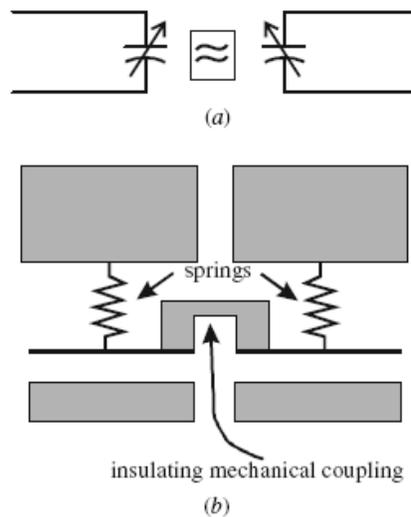
Fig. 3 Schematic of a MEMS dc–dc Converter

In DC–DC converter uses a MEMS variable capacitor operated by an actuator, in a charge pump configuration. Even in conventional DC–DC converter circuits. A key challenge in achieving integrated switching dc–dc converters is to realize on-chip inductors of sufficient quality factor (Q) reported advantages of MEMS style fabrication includes;

(i)   Planar coils in conventional CMOS, the greater three-dimensionality of MEMS structures allows solenoids to be fabricated.

(ii)   Provide higher inductance for a given conductor length, because of improved flux coupling and offer higher Q.

(iii)   Possibility of fabricating the solenoid with its axis parallel to the wafer surface with rectangular windings built up as three levels of metallization.

MEMS provide a wide range of uses in integrated power systems and associated with circuitry make exploitation more practicable. To realize the potential of MEMS in power supplies, the cost∕benefit ratio of adding MEMS processing is significantly improved when a number of related MEMS functions are co-integrated within single modules. These functions include sensing, as well as the power functions. The sensing functions may add requirements for enhanced circuit protection, particularly as sensors often need to interface to the local environment and increase the risk of electrical interference. An interconnection of MEMS and other modules in a power supply for portable electronics module is shown

in Figure 4. MEMS voltage converter consists of a variable capacitor which is mechanically coupled to a micro-actuator. The charging and conversion states of the capacitor and (*b*) gives a timing diagram for the switch control signals shown in Figure 5.
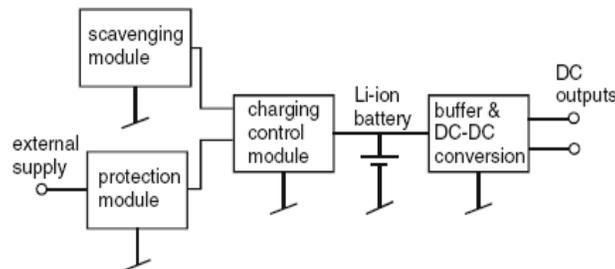
Fig. 4 MEMS Interconnection and Electronics Power Supply Schematic
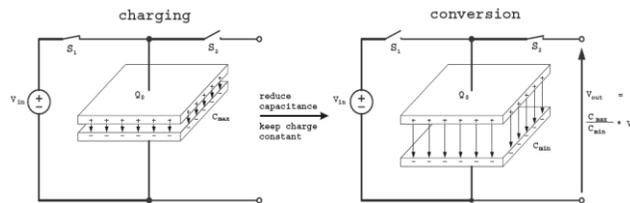
Fig. 5 MEMS DC converter charging and conversion states

A schematic of the proposed MEMS voltage converter is shown in Figure 6.
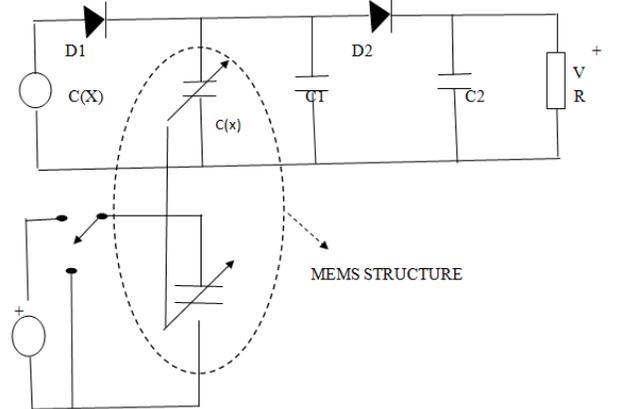
Fig. 6 Implementation of Voltage converter

The core element is the variable capacitor C(x) which is mechanically coupled to an electrostatic micro-actuator. Operation of the switch Φ causes the actuator to change capacitance by moving one of the electrodes of the capacitor. The electrode movement is restricted to a minimum and a maximum displacement that corresponds to a capacitance of Cmin and Cmax, respectively. Thus, the variable capacitor allows for a maximum voltage multiplication factor of

$$Mc = \frac{Cmax}{Cmin}$$

The capacitance variation can either be based on a variable electrode gap (transverse structure) or by a change in effective electrode area (comb structure). Both approaches are suitable to serve both as capacitor and actuator. This leads to four possible capacitor-actuator combinations and each of them can be arranged in one of two different modes: In "active reduction" mode, the capacitor is charged and then reduced in capacitance by activation of the electrostatic actuator. Conversely, in the "active increase" mode, the electrostatic actuator is used to firstly increase the capacitance and at the same time to load the compliant mechanical suspension of the structure. Then, the capacitor is charged and subsequent

deactivation of the actuator prompts the mechanical suspension to reduce the working capacitance and thus increase the voltage. The device can be represented as an equivalent voltage source of magnitude,

$$Vo = \frac{(Mc + C'p)}{(1 + C'p)} * Vin + \frac{(Mc + 1 + C'p)}{(1 + C'p)} * Vd$$

where, $C'p = \frac{C1}{Cmin}$ is the relative parasitic capacitance and VD the diode forward bias. The equivalent source resistance is,

$$R = \frac{1}{(C1 + Cmin) * Fclk}$$

The actuator is operated at a clock frequency Fclk.

5. SUGAR - MEMS SIMULATION PROGRAM

MEMS have leveraged the integrated-circuit community's fabrication technique. A wide range of circuit designers regularly use circuit simulation tools like SPICE, while MEMS designers often resort to back-of-the-envelope calculations. For the development of IC CAD tools has gone hand-in-hand with the development of IC processes. Tools for simulation play a role in future advances in the design of complicated MEMS devices. The tools available are,

     (i)   Intellisuite
     (ii)   COMSOL
     (iii)   Convertor ware
     (iv)   ANSYS

Some open source tools are,

     (i)   SUGAR
     (ii)   NODAS
     (iii)   via SABER

SUGAR is an open source simulation tool for MEMS based on nodal analysis techniques of integrated circuit simulation. Beams, electrostatic gaps, circuit elements, and other elements are modeled by small, coupled systems of differential equations. It inherits name from spice that used for MEMS and describe a device in a compact netlist format and simulate the device's behavior. The main components of SUGAR are,

(i) Netlist Interpreter (Based on LUA programming).
(ii) Models written in Mat Lab or C language (Describing the characteristics of different components)
(iii) Command line(for interaction and visualization of specific component)
(iv) GUI (for interaction and visualization of specific component)
(v) SUGAR core (to handle Nodes, elements, Mesh assembly and analysis of the device)

5.1 Use SUGAR from MATLAB

To design a long cantilever, it needs file that describing the cantilever or an input file (a netlist) as shown in given example.

```
use ("mumps.net")
use ("stdlib.net")
A = node {0, 0, 0; name = "A"}
B = node {name = "B"}
anchor { A ; material=p1, l=10u, w=10u }
beam3d {A, B; material=p1, l=100u, w=2u}
f3d {B; F=50u, oz =90}
```

(save this netlist in the file called cantilever.net. (*.net describes the characteristics of the component)).

SUGAR has the effect the force on the cantilever beam that described to Create effect_canti.m file and the effect of static (DC) analysis, as example,

```
net = cho_load('cantilever.net');
q = cho_dc(net);
cho_display(net, q);
```

SUGAR process the netlist description in cantilever.net and the result is a data structure stored in the net variable that describes the device to other SUGAR routines.

6. RESULTS AND DISCUSSION

The MEMS based DC-DC converter design is simulated using SUGAR, using the MUMPS process and the results are shown in Figure 7. The layout is not to scale but illustrates the principle: A central beam is suspended by folded flexures and connected to electrical ground potential. In the lower section it carries a number of electrode fingers that form a transverse capacitor. The upper section is a comb-drive actuator that is used to perform an active reduction of the working capacitance. The darker shaded areas are anchors of oxide while the lighter coloured parts are released from the substrate and free to move. The net file is given in Appendix-1. The implemented modules include;

(i)   Suspended Central Beam
(ii)   Transverse Capacitance nodes : Fixed ARM and Movable ARM
(iii)   Comb structure
(iv)   Anchor 1 to Anchor 4
(v)   Non Movable Beam
(vi)   Comb Structure Lower ARM
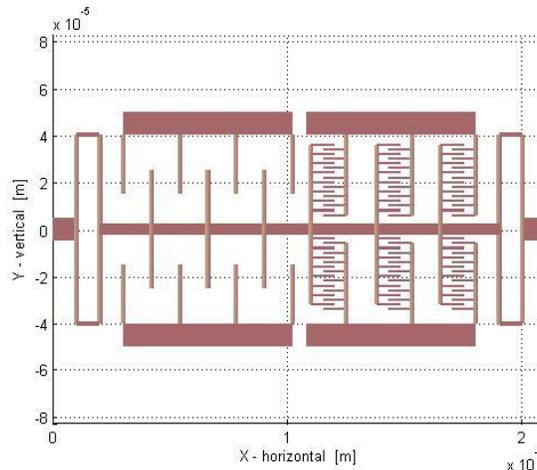
Fig. 7 Simulated variable capacitance of the DC-DC converter using MEMS Sugar Simulator

7. CONCLUSION

The proposed MEMS based DC-DC converter has a major advantage that the voltage converter holds potential benefit for applications that hinge on process integration and miniaturization. The control and actuation capacitances are mechanically coupled. We can attain high aspect ratio that proves beneficial for the creation of large electrodes perpendicular to the wafer plane, thus optimizing volume utilization. Potential problems of MEMS layout such as each electrode of the transverse capacitor has an electrostatic field on both sides which leads to a significant reduction of the voltage multiplication factor and the oxide anchors introduce a relatively high parasitic capacitance could be taken for future study.

- ## 8. REFERENCES

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Appendix -1: Net file Pseudo Code

```
use "mumps.net"
use "stdlib.net"
node{0,0,0;name="A"}
node{0.00001,-0.00004,0;name="A1"}
node{0.00002,-0.00004,0;name="A3"}
node{0.0002,0,0;name="B"}
node{0.0002,-0.00004,0;name="A2"}
node{0.00019,-0.00004,0;name="A4"}

--Suspended Central Beam
node{0.00002,0,0;name="CB1"}
node{0.00019,0,0;name="CB2"}

--Transverse Capacitance nodes
--Fixed ARM
node{0.00003,0.000045,0;name = "TC1"}
node{0.00003,-0.000045,0;name = "TC2"}
node{0.00018,0.000045,0;name="TC3"}
node{0.00018,-0.000045,0;name="TC4"}
node{0.00003,0.000040,0;name = "BM0"}
node{0.000054,0.000040,0;name="BM2"}
node{0.000078,0.000040,0;name="BM4"}
node{0.000102,0.000040,0;name="BM6"}
node{0.00003,-0.000040,0;name = "BM00"}
node{0.000054,-0.000040,0;name="BM20"}
node{0.000078,-0.000040,0;name="BM40"}
node{0.000102,-0.000040,0;name="BM60"}

--Movable ARM
node{0.000042,0,0;name="MA1"}
node{0.000066,0,0;name="MA2"}
node{0.000090,0,0;name="MA3"}

--Comb structure
node{0.000110,0.00002,0;name="CM1"}
node{0.000125,0.00002,0;name="CM2"}
node{0.000138,0.00002,0;name ="CM3"}
node{0.000153,0.00002,0;name="CM4"}
node{0.000165,0.00002,0;name="CM5"}
node{0.000180,0.00002,0;name="CM6"}
node{0.000110,-0.00002,0;name="CM11"}
node{0.000125,-0.00002,0;name="CM21"}
node{0.000138,-0.00002,0;name ="CM31"}
node{0.000153,-0.00002,0;name="CM41"}
node{0.000165,-0.00002,0;name="CM51"}
node{0.000180,-0.00002,0;name="CM61"}

--Suspended Central Beam
beam3d{node "CB1",node "CB2";material = p1,l=170u,w=5u,oz=0}

--Transverse Capacitance

--Anchor 1
```

anchor{node "TC1"; material = p1,l=72u,w=10u}
--Anchor 2
anchor{node "TC2"; material = p1,l=72u,w=10u}
--Anchor 3
anchor{node "TC3"; material = p1,l=72u,w=10u,oz=180}
--Anchor 4
anchor{node "TC4"; material = p1,l=72u,w=10u,oz=180}

--Non-movable Beam
beam3d{node"BM0",node"BM1";material = p1,l=25u,w=2u,oz=-90}
beam3d{node"BM2",node"BM3";material = p1,l=25u,w=2u,oz=-90}
beam3d{node"BM4",node"BM5";material = p1,l=25u,w=2u,oz=-90}
beam3d{node"BM6",node"BM7";material = p1,l=25u,w=2u,oz=-90}
beam3d{node"BM00",node"BM10";material = p1,l=25u,w=2u,oz=90}
beam3d{node"BM20",node"BM30";material = p1,l=25u,w=2u,oz=90}
beam3d{node"BM40",node"BM50";material = p1,l=25u,w=2u,oz=90}
beam3d{node"BM60",node"BM70";material = p1,l=25u,w=2u,oz=90}

--Movable ARM
beam3d{node"MA1",node"MA4";material = p1,l=25u,w=2u,oz=90}
beam3d{node"MA1",node"MA5";material = p1,l=25u,w=2u,oz=-90}
beam3d{node"MA2",node"MA6";material = p1,l=25u,w=2u,oz=90}
beam3d{node"MA2",node"MA7";material = p1,l=25u,w=2u,oz=-90}
beam3d{node"MA3",node"MA8";material = p1,l=25u,w=2u,oz=90}
beam3d{node"MA3",node"MA9";material = p1,l=25u,w=2u,oz=-90}

--COMB STRUCTURE
comb2d{node "CM1",node "CM2";material=p1,l=5u,w=1u,N=8,L=10u,oz=0,gap=1u}
beam3d{node"CM1",node"Cm0";material = p1,l=20u,w=2u,oz=-90}
beam3d{node"CM2",node"Cm1";material = p1,l=20u,w=2u,oz=90}
comb2d{node "CM3",node "CM4";material=p1,l=5u,w=1u,N=8,L=10u,oz=0,gap=1u}
beam3d{node"CM3",node"Cm2";material = p1,l=20u,w=2u,oz=-90}
beam3d{node"CM4",node"Cm3";material = p1,l=20u,w=2u,oz=90}
comb2d{node "CM5",node "CM6";material=p1,l=5u,w=1u,N=8,L=10u,oz=0,gap=1u}
beam3d{node"CM5",node"Cm4";material = p1,l=20u,w=2u,oz=-90}
beam3d{node"CM6",node"Cm5";material = p1,l=20u,w=2u,oz=90}

---Lower Comb
comb2d{node "CM11",node "CM21";material=p1,l=5u,w=1u,N=8,L=10u,oz=0,gap=1u}
beam3d{node"CM11",node"Cm01";material = p1,l=20u,w=2u,oz=90}
beam3d{node"CM21",node"Cm11";material = p1,l=20u,w=2u,oz=-90}
comb2d{node "CM31",node "CM41";material=p1,l=5u,w=1u,N=8,L=10u,oz=0,gap=1u}
beam3d{node"CM31",node"Cm21";material = p1,l=20u,w=2u,oz=90}
beam3d{node"CM41",node"Cm31";material = p1,l=20u,w=2u,oz=-90}
comb2d{node "CM51",node "CM61";material=p1,l=5u,w=1u,N=8,L=10u,oz=0,gap=1u}
beam3d{node"CM51",node"Cm41";material = p1,l=20u,w=2u,oz=90}
beam3d{node"CM61",node"Cm51";material = p1,l=20u,w=2u,oz=-90}