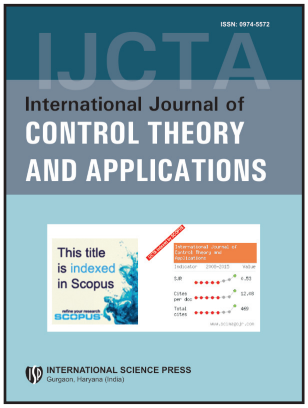

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Design and Develop a Novel DC-DC Power Converter using SUGAR Simulator

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Abstract: Power systems and machines integration is one of the rapidly growing research areas nowadays. Since energy resources become more popular in the electrical industry, it is essential to utilize them in an effective manner. Various applications are suing DC-DC power converters whereas the applications involves supplying power to the PC, office equipment, telecommunication equipment, spacecraft power systems and DC-motor drives. In this paper, it is motivated to regulate the power supply it is aimed to design a new Micro-Electro-Mechanical-System (MEMS) of an integrated DC-DC converter which is derived electro statically. One of the main advantages of this converter is two mechanical switches are added additionally to replace the conventional diodes to provide no-leakage power, low power consumption with synchronous operation. The features of this MEMS DC-DC converter comprise of tunable capacitor, capacitors with different gaps and a complete mathematical model of the DC-DC converter is described. Also the behavior of the converted model is simulated and investigated using various mathematical methods to evaluate the performance.

Keywords: DC-DC Converter, Micro-Electro-Mechanical-System, Mechanical Switches.

1. INTRODUCTION

The two stages which are involved in the process of electrical power generation from mechanical vibrations are: a mechanical resonator and an electromechanical transducer. Initially, a proof mass is linked with the environmental vibrations through an elastic link: the resonator is constituted by the mass and the spring which are present in all vibration energy reapers. On account of this versatile coupling with the vibrating frame, the mass is moved and mechanical energy is gathered by the resonator. The second stage comprises in the transformation of this mechanical energy into electric energy. For this reason, an electromechanical transducer ought to apply a damping force on the mass, i.e. a negative work should be performed on the mechanical system. The electrical energy flow is managed by the conditioning circuit such that maximum energy would be accumulated in the reservoir which supplies the load. The electrical context is created by the conditioning circuit additionally which is essential for the operation of the electromechanical transducer.

A DC-to-DC converter is an electronic circuit in which a source of direct current (DC) is converted from one voltage level to another and it is described as a class of the power converter. It is a group of switched-mode power supply (SMPS) having not less than two semiconductors (a diode and a transistor) and at least one energy storage element, a capacitor, inductor, or the two in combination. Normally, the filters which are made of capacitors (sometimes in combination with inductors) are added to the output of the converter for reducing the output voltage ripple.

A power switch, an inductor, and a diode is used by a switching regulator for transferring the energy from input to output. The step-down (buck) converter, a step-up (boost) converter, or an inverter could be formed by rearranging the fundamental components of the switching circuit. The energy transfer is regulated and a constant output is maintained within normal operating conditions by carefully nesting the feedback and control circuitry around these circuits. A single-pole double-throw (SPDT) switch is associated with the dc input voltage V_g as depicted in Figure 1. When the switch is in position 1, the switch output voltage $v_s(t)$ is equivalent to V_g and when the switch is in position 2, it is equivalent to zero. The switch position fluctuates occasionally, with the end goal that $v_s(t)$ is a rectangular waveform having period T_s and duty cycle D. The dc-dc converter shown in Figure 1 comprises of a switch system which reduces the dc component of voltage and a low-pass filter that expels the high-frequency switching harmonics.

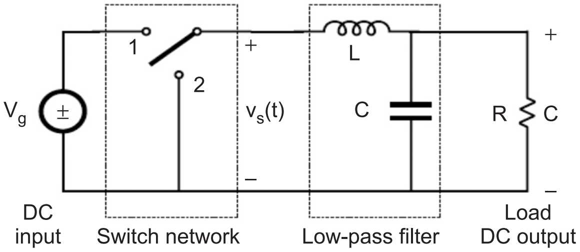

Figure 1: DC-DC Converter with a switch network

A DC input, DC output are parallel connected with switch 1 and 2, resistance L parallel to a capacitor C is shown in the Figure 1.

The entire contribution of the paper is:

- Reduce the time, hardware complexity and reduce power consumption by
- Desing a new DC-DC converter is mathematical model
- Avoid diodes using Mathematical model
- Use synchronous operation

The general idea of using a mathematical model over SUGAR simulation is to obtain a reduced order model for a dynamic system in order to replace the existing system by an approximating system with very low state-sapce dimension. The steady state analysis and transient analysis is applied to get an accurate and effective reduced order model. The result of these models can reduce the computational time, aggressive design strategies and hardware complexity. This kind of computational prototype tool can make the designers try “What if” practical in hours instead of days. DQM or Garlirkin subspace methods are recent numerical methods which reduced order model over large scale dynamic systems. They have guide to obtain a major breakthrough in the field.

2. LITERATURE SURVEY

The bulkier components in a power converter are the passive energy storage and transfer components such as inductors, capacitors and transformers. Much effort has been pivoted on miniaturizing these components and augmenting the power density of the power converter systems. In [1-3], various studies has been investigated on the optimized structures, materials and fabrication techniques for on-chip integration of these bulky components. With the advancement of the MEMS technology, a reasonable pattern of utilizing mechanical structures to acknowledge electrical functionalities can be remarked. The typical examples include switches [4, 5], oscillators [6,7], etc. The DC voltage is converted into another DC voltage by the integrated MEMS converter meaning the step-up or step-down conversion using a variable capacitor [8, 9]. The electrostatically determined microstructure is appropriate to be utilized in monolithic resonant DC-DC converter [10]. Instead of an LC circuit and a transformer, the mechanical resonant structure is used in [10]. The micro-resonator drivers [11], scientific instruments [12], and micro-propulsion units [13] might be supplied by using a DC-DC converter.

Both the inter-digitated comb fingers and parallel plates are used in the previous researches [8, 14, 15, 16] to design and model the MEMS DC-DC converter. A lumped model is presented by all these works to model the converter and they have utilized diodes or active contact circuits for storing the electric energy. A new design of DC-DC converter as well as its associated complete mathematical model has been introduced in this paper. Also, a complete mathematical model has been proposed and the traditional diode is replaced by mechanical switches which have the advantage of zero leakage current, low power consumption and synchronous operations. Next, the mathematical model of the proposed work has been tackled with the two different methods (differential quadratic method (DQM) and Galerkin method).

The proposal for an AC voltage reference based on a capacitive micro electromechanical system (MEMS) were first published in 1998 [17-18]. The MEMS AC voltage reference is dependent on the characteristic pull-in point of the MEMS component. This pull-in point relies only on the component geometry and material properties of single crystal silicon. Some of the advantages of MEMS components in reference applications are good stability [19], low noise, large operating voltage range, small size, and low power consumption. The gadgets of a stable AC voltage reference are realized easily than the electronics of a DC voltage reference. In order to bias the component to the pull-in position, an AC current drive is needed for the AC voltage reference while the DC reference requires a feedback circuit [19]. Besides, cathode charging impacts are negligible when utilizing an AC motion for the incitation of the moving electrode [20].

A number of micro-devices could be benefitted from a completely integrated MEMS voltage converter, which means up their low DC input voltage to higher levels. For instance, the effectiveness of micro-resonators can be expanded by utilizing a high DC inclination voltage [21] and electrical noise levels in capacitive accelerometers can be reduced in a parallel fashion [22]. The space applications such as scientific instruments [23] and micro-propulsion units [24] aboard satellites requires high DC voltages. A strong need for miniaturized voltage converters is created by the relative low output voltage of solar panels and the trend towards the microsatellites.

Either the boost converters or charge pumps are used for performing the stepping up of DC voltages. The boost converters depends on an electrical inductance and hence it is difficult to integrate. The Charge pumps [25] comprises of a number of capacitors which are interconnected by MOS diodes and they are widely utilized in integrated circuits. Notwithstanding, the amount of required capacitors is linearly increased with the desired voltage multiplication factor, thus requiring much wafer surface area. The voltage conversion approach described here is a novel and only a few previous work exists about MEMS voltage converters. In [26, 27], the authors had described about some of the approaches to replace the inductor in boost converters by a micro-machined variable capacitor.

3. PROBLEM STATEMENT

One of the software package used for 3D MEMS simulation is SUGAR where follows the SPICE and MATLAB software family circuit simulation. This software tested and verified by software and electrical and electronics experts using various kind of analysis. MEMS problems can be solved in SUGAR more accurately than finite element models. In this paper the model and the design data is taken from SUGAR 2.0 software where it comprises of various features like gap analysis and user defined mathematical model analysis and so on. In this paper the following mathematical problem is solved in SUGAR and the results are obtained.

The considered MEMS converter converts one DC voltage into another DC voltage meaning step-up or step-down using a variable capacitor [1,2]. One of the suitable microstructure which is derived electro statically is more suitable for monothlic resonant DC-DC converter [3] whereas this converter uses mechanical resonant structure instead of an LC circuit and a transformer. It can also be used for supplying micro-resonator drives, various scientific instruments and micro-units. In some of the earlier research works to desing a new model MEMS DC-DC converters, integrated comb fingers and parallel plated are used. Also they all used diodes, contact circuits for storing electric energy. But in this paper it is aimed to desing new DC-DC converter model related to a mathematical model. The mathematical model of the converter is presented here and diodes are replaced using mechanical switches where it supports zero leakage current and reduce the power consumption using synchronous operations.

Figure 2 shows the desing of the proposed DC-DC converter where it mainly function on two capacitor variables as C_1 and C_2. At the left and right end, a cantilever beam is fixed at the substrate and a rigid plate is attached with mass (M). A non-linear electrostate force is generated while electrical voltage is applied between the lower and mobile plate and it makes movement of mobile plate which is represented in Equ-(1).

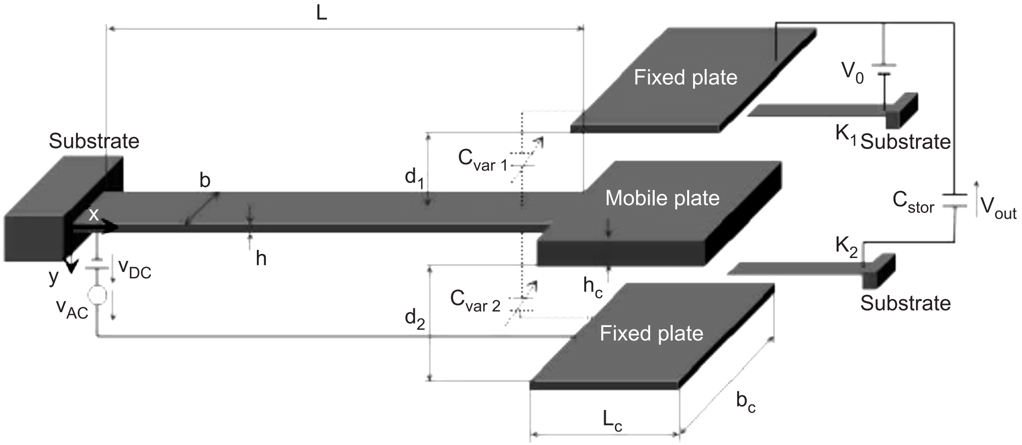

Figure 2: Schematic of the MEMS DC-DC converter

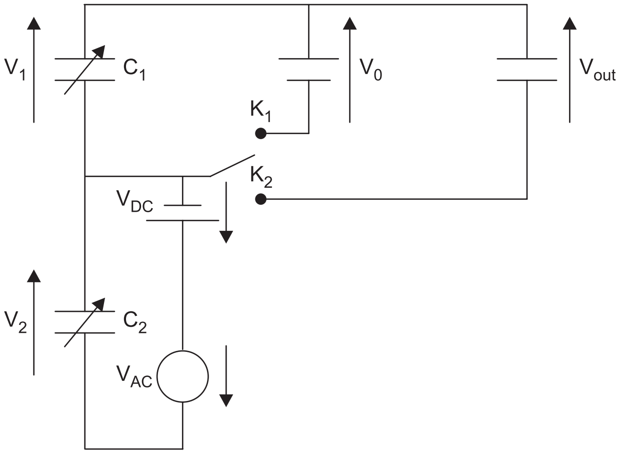

Figure 3: Its electric schema

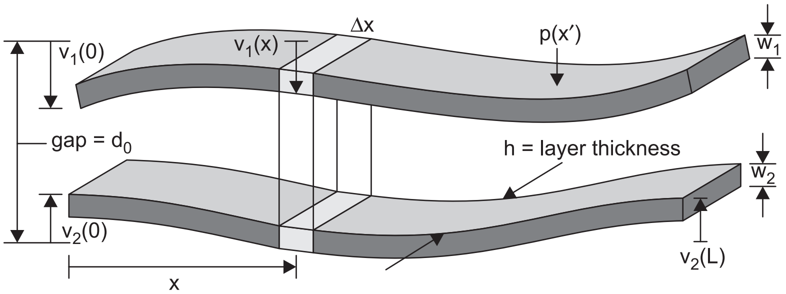

Figure 4: Electro static Gap

Also the electro static gap between the mobile plates is shown in Figure 4.

$$\mathrm{EI}\frac{\partial^4 y(x,t)}{\partial x^4}+\mathrm{C}\frac{\partial y(x,t)}{\partial t}+\rho\mathrm{A}\frac{\partial^2 y(x,t)}{\partial t^2}=0$$

At $\mathrm{Y}_{\min} \le y \le \mathrm{Y}_{\max}$

$$\mathrm{EI}\frac{\partial^4 y(x,t)}{\partial x^4}+\mathrm{K}y(\mathrm{L},t)+\mathrm{C}\frac{\partial y(x,t)}{\partial t}+\rho\mathrm{A}\frac{\partial^2 y(x,t)}{\partial t^2}=0 \tag{1}$$

At $y \le \mathrm{Y}_{\max}$

$$\mathrm{EI}\frac{\partial^4 y(x,t)}{\partial x^4}+\mathrm{K}y(|\mathrm{L},t)+\mathrm{C}\frac{\partial y(x,t)}{\partial t}+\rho\mathrm{A}\frac{\partial^2 y(x,t)}{\partial t^2}=0$$

At $y > \mathrm{Y}_{\min}$

$$\mathrm{Y}(0,t)=\frac{\partial y(0,t)}{\partial x}=\mathrm{Y}(\mathrm{L},t)=\left.\frac{\partial y(\mathrm{L},t)}{\partial x}\right|=0 \tag{2}$$

$$\mathrm{EI}\frac{\partial^2 y(\mathrm{L},t)}{\partial x^2}=-\mathrm{M}\frac{\mathrm{L}_c}{2}\frac{\partial^2 y(\mathrm{L},t)}{\partial t^2}-\left[\mathrm{M}\left[\frac{\mathrm{L}_c}{2}\right]^2+\mathrm{J}\right]\frac{\partial(\partial^2 y(\mathrm{L},t))}{\partial x\partial t^2}$$

$$+\frac{\varepsilon b_c(\mathrm{V}_{\mathrm{DC}}+\mathrm{V}_{\mathrm{AC}})^2}{2\left[\frac{\partial y(\mathrm{L}),t}{\partial x}\right]^2}\left[\frac{\mathrm{L}_c\frac{\partial y(\mathrm{L},t)}{\partial x}}{d_2-y(\mathrm{L},t)-\mathrm{L}_c\frac{\partial y(\mathrm{L},t)}{\partial x}}-\ln\left[\frac{d_2-y(\mathrm{L},t)}{d_2-y(\mathrm{L},t)-\mathrm{L}_c\frac{\partial y(\mathrm{L},t)}{\partial x}}\right]\right] \tag{3}$$

$$\mathrm{EI}\frac{\partial^3 y(\mathrm{L},t)}{\partial x^3}=\mathrm{M}\frac{\partial^2 y(\mathrm{L},t)}{\partial t^2}+\mathrm{M}\left[\frac{\mathrm{L}_c}{2}\right]\frac{\partial(\partial^2 y|(\mathrm{L},t))}{\partial\partial t^2}-\frac{\varepsilon b_c(\mathrm{V}_{\mathrm{DC}}+\mathrm{V}_{\mathrm{AC}})^2}{2\left[\frac{\partial y(\mathrm{L},t)}{\partial x}\right]^2}$$

$$\left[\frac{1}{d_2-y(\mathrm{L},t)-\mathrm{L}_c\frac{\partial y(\mathrm{L},t)}{\partial x}}-\frac{1}{d_2-y(\mathrm{L},t)}\right] \tag{4}$$

Also the boundary condition is represented in equ-(2) to equ-(4). At high position ($\mathrm{Y}_{\max}$) related to maximum value ($\max(\mathrm{C}_1)$) the switch K_1 is turns on. It is well known that, K_1 is a cantilever with stiffness K which is added to equ-(1). Here the capacitor C_1 is connected into the initial voltage V_0 and a charge Q is injected in it. The cantilever system reserves the direction as well as both switches K_1 and K_2 because of the drive signal ($V_{DC} + V_{AC}$) whereas K_1 and K_2 are off maintained as a constant charge Q. At lower position (Y_{min}), corresponds to the lowest value (min(C_1)) turns on the switch K_2 and inject the charge Q into the storage capacitor C_s. The resultant voltage V_{out} obtained from the device is expressed as

$$V_{out} = \left(\frac{C_{max}}{C_{min}}\right) \times V_0$$

In this paper the MEMS DC-converter is designed using a DC voltage

$$V_{DC} = 5 \text{ V}$$

Bi-polar square waveform voltage

$$V_{AC} = \pm 5 \text{ V}$$

the frequency is

$$f = 11{,}728 \text{ KHz}$$

which is equal to the natural frequency of the common MEMS converter structure. Figure 3 shows the schema of the electrical system illustrates the sufficient explanation of the system. Both capacitors C_1 and C_2 are expressed as:

$$C_1 = \frac{\varepsilon b_c L_c}{(d_1 + Y(L, t))}$$

$$C_2 = \frac{\varepsilon b_c L_c}{(d_2 + Y(L, t))}$$

The entire parameters of the MEMS DC-DC converter are given in Table 1. The switching method of the DC-DC converter in terms of low-high voltage and time is shown in Figure 5.

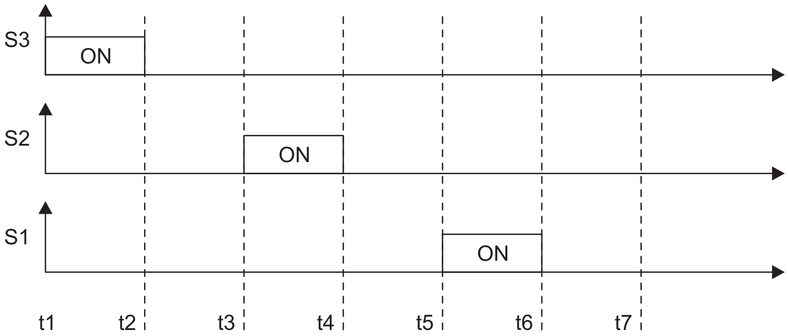

Figure 5: Switching At Stipulated Time Interval

The Equ-(1) and the boundary constraint (2-4) are solved using DQM or Garlirkin method.

From the model (Figure 6) the new design is created by modifying the old one. In the new desing MEMS has single input and multi-output voltage level shifter. The conversion of low level voltage to high level voltage depends on the electrostatic transduction of C1 and C2 by interdigitized comb fingers. In this paper we present the design of a MEMS single-input multi-output voltage level shifter. The low-voltage to high-voltage conversion is based on the elec-trostatic transduction of variable capacitors built using interdigitated comb fingers. The new DC-DC model is simulated in MATLAB software and the results are verified. A sample Simulink model taken

Table 1
List of Legend

Position of the lower switch	$Y_{min} = -10\ \mu m$
Position of the upper switch	$Y_{max} = 10\ \mu m$
Displacement of the mobile plate in Y direction	$Y(x, t)$
Derivative with respect to *x*	$\frac{\partial y(x,t)}{\partial x}$
Derivative with respect to *t*	$\frac{\partial y(x,t)}{\partial t}$
Derivative with respect to *x* at L	$\frac{\partial y(L,t)}{\partial x}$
Derivative with respect to *t* at L	$\frac{\partial y(L,t)}{\partial t}$
Derivative with respect to *x* at point 0	$\frac{\partial y(0,t)}{\partial x}$
Displacement of the mobile plate at point 0 and L respectively	$Y(0, t)$, $Y(L, t)$

Table 2
Geometrical parameters of the MEMS converter

Cantilever Length	$L = 250\ \mu m$
Plates Length	$L_c = 50\ \mu m$
Cantilever, Lower and Upper plate thickness	$h = 1.5\ \mu m$
Mobile plate thickness	$h_c = 10\ \mu m$
All plates width	$b_c = 40\ \mu m$
Cantilever beam width	$b = 5\ \mu m$
Gap between the lower plate and mobile plate	$d_2 = 15\ \mu m$
Gap between the Upper plate and mobile plate	d_1 depends on the design
Elasticity Modulus	$E = 166$ GPa
Density	$\rho = 2332\ Kg/m^3$
Perimitivity of the free space	$\varepsilon = 8.851 \times 10^{-12}$ F/m
Mass	$M = 1.165 \times 10^{-14}$ Kg
K1 and K2 switch stiffness	$K = 191$ N/m
Mass moment of Intertia of the mobile plate	$J = \frac{1}{3} ML_c^2$

as the reference for creating a new model is shown in Figure 6. The circuit taken from the reference model is modified according to MEMS concept and created for simulation. The following Figure 7 shows the effects of the switch cantilever. Also it describes the switches are behaving as stopper up to the limit where the dislocation of the central plate and prevents ensuing short circuit. The mobile plate oscillation is shown without switches between $-14.135\ \mu m$ and $14.135\ \mu m$.

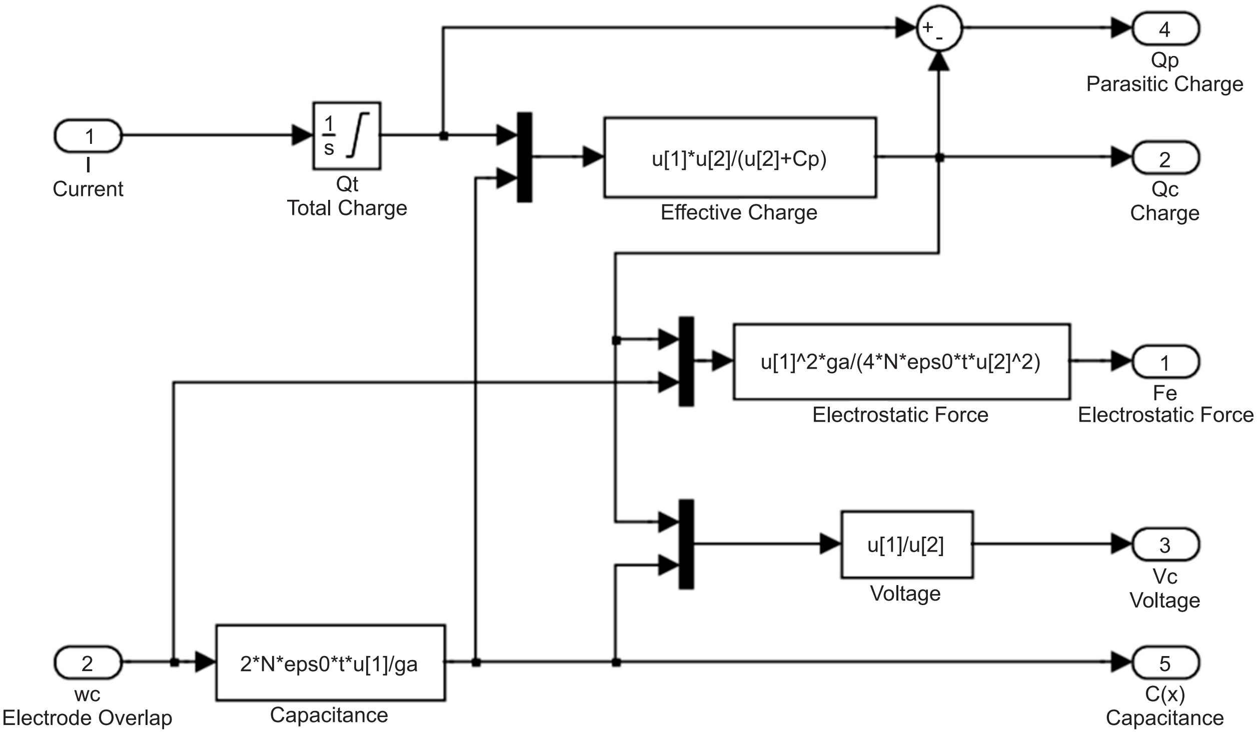

Figure 6: Sample DC-DC convert Model

Here the switches are placed at $Y_{min} = -10$ µm and $Y_{max} = 10$ µm and the oscillation varies from −7.35 µm to 7.35 µm. Additionally the mobile plates take 40.80 µs and this time duration is more sufficient to charge anddis-charge the capacitor C_1. Figure-5 illustrates the changes occur in the V_{out} having starting distance d_1 between the plates of C_1. The results show that V_{out} changes from 10 V to 50 V where the initial voltage of V_{out} is 5 V. Accordingly the gain voltage is also charged from 100% to 1000% where they are significant.

The time required to convert the initial voltage V_0 to output voltage V_{out}. The experimental result obtained from the simulation interms of time is shown in Figure 7. From Figure 7, it is clear and noticed that T_c obtained from the proposed design is 21.01 ms. From the exising model the obtained T_c is 22.73 ms whereas the new model obtained less time than the existing one.

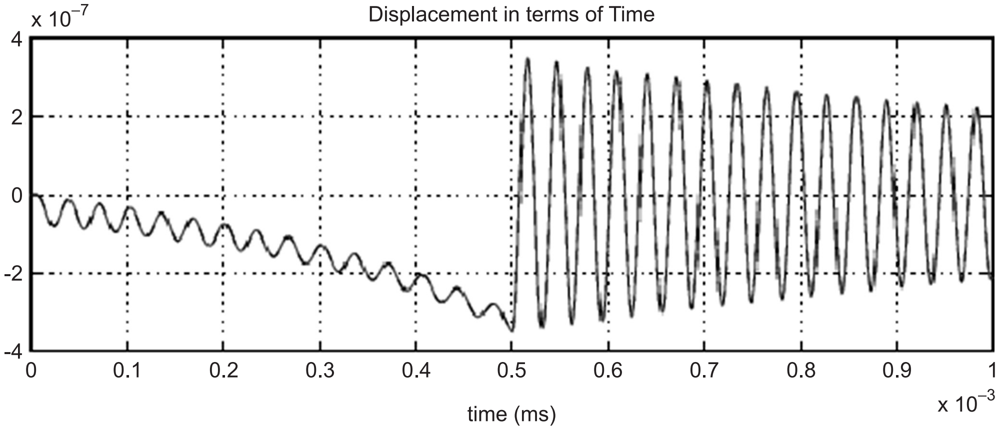

Figure 7: Displacement versus Time

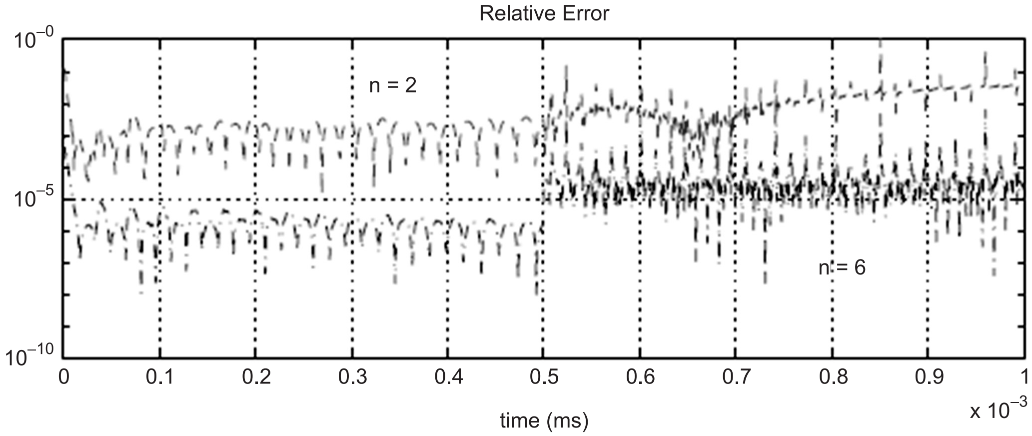

Figure 8: Relative Error versus Time

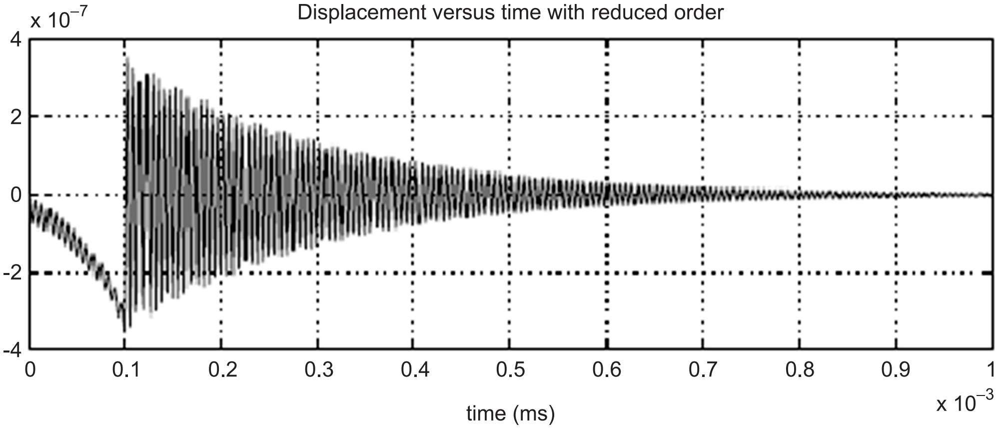

Figure 9: Displace versus Time with Reduced Order

From the Figures 7 to 9, it is noticed that the displacement in y direction is selected from node C. The voltage is changed from initial voltage starts from device to resonate. When the voltage increases linearly the gap decreases non-linearly according to the electro static force increases. The electro static force increases proportionally to 1/gap $(q)^2$. It also affects the osicillation to increase. Figure 7 shows the displacement versus time. Figure 9 shows the decays to equilibrium. Same time the accuracy of the order reduced model is shown in Figure 8. From the above Figures 7 to 9 it is very clear that the proposed model provide more accuracy in terms of switching and voltage generation.

4. CONCLUSION

The main objective of this paper is to provide a new design for MEMS DC-DC converter with low hardware complexity and low power consumption. In order to do this a synchronous operation based DC-DC converter circuit is designed. It uses mechanical switches where it replaces conventional diodes and reduce the hardware complexity. Also the entire model is designed using mathematical model reduces power consumption based operation. The entire model converters 5 V to more than 50 V within less conversion time.

REFERENCES

[1] Gardner D.S., Schrom G, Paillet F, Jamieson B, Karnik T and Borkar S (2009). Review of on-chip inductor structures with magnetic films IEEE Trans. Magn. **45** 4760-6.

[2] Mathuna S C O, O'Donnell T, Wang N and Rinne K (2005). Magnetics on silicon: an enabling technology for power supply on chip IEEE Trans. Power Electron. **20** 585-92.

[3] Lee J, Hong Y K, Bae S, Jalli J, Park J, Abo G S, Donohoe G W and Choi B C (2011). Integrated Ferrite Film Inductor for Power System-on-Chip (PowerSoC) Smart Phone Applications IEEE Trans. Magn. **47** 304-7.

[4] Fang D-M, Jing X-M, Wang P-H, Zhou Y and Zhao X-L (2008). Fabrication and dynamic analysis of the electrostatically actuated MEMS variable capacitor Microsyst. Technol. **14** 397-402.

[5] Keimel C, Claydon G, Li B, Park J and Valdes M E (2011). Micro-Electromechanical-System (MEMS) based switches for power applications IEEE Proc. Ind. and Commercial Power Syst. Tech. Conf. (Newport Beach, CA) pp 1-8.

[6] Yu A, Liu A and Zhang Q (2005). Tunable MEMS LC resonator with large tuning range Electron. Lett. **41** 855-7.

[7] Kao P-H, Dai C-L, Hsu C-C and Lee C-Y (2009). Fabrication and Characterization of a Tunable In-plane Resonator with Low Driving Voltage Sensors **9** 2062–75.

[8] L. Li, M. Begbie and D. Uttamchandani, "Single-input, dual-output MEMS DC-DC converter" Electronics Letters 19th July 2007 Vol. 43, No. 15.

[9] Sahar Ghandour, Ghislain Despesse, Skandar Basrour "Design of a New MEMS DC/DC Voltage Stepdown Converter" Proceding of 8th IEEE international new case, Montreal, 20-23 Jun 2010.

[10] S.V. Cheong et. al., "Inductorless DC-to-DC Converter with High Power Density", IEEE Trans. Ind. Electronics, Vol. 41, No. 2, 1994.

[11] Wang, K., and Nguyen, C.T.C.: "High-order medium frequency micromechanical filters", J. Microelectromech. Syst., 1999, 8, pp. 534-557.

[12] Nordholt, J.E., Young, D.T., and Funsten, H.O.: 'Plasma experiment for planetary exploration (PEPE)'. DS1 IEEE Aerospace Conf. Proc., 2000, Vol. 7, pp. 597-607.

[13] Larangot, B., Conedera, V., Dureuil, P., DO Conto, T., and Rossi, C.: "Solid propellant microthruster: an alternative propulsion device for nanosatellite". Aerospace Energetic Equipment Conf., Avignon, France, 2002.

[14] Haas, C.H., and Kraft, M., "Modelling and analysis of a MEMS approach to dc voltage step-up conversion", J. Micromech. Microeng., 2004, 14, pp. S114-S122.

[15] Hill, M., and Mahony, C.O., "Modelling and performance evaluation of a MEMS dc=dc converter", J. Micromech. Microeng., 2006, 16, pp. S149-S155.

[16] Cottone, P. Basset, F. Marty, D. Galayko, L. Gammaitoni and T. Bourouina, "Electrostatic Generator with free micro-ball and elastic stoppers for low-frequency vibration harvesting" MEMS 2014, San Francisco, CA, USA, January 26-30, 2014.

[17] Suhonen, H. Seppä, A.S. Oja, M. Heinilä, and I. Näkki, "AC and DC voltage standards based on silicon micromechanics," in CPEM'98 Conf. Dig., 1998, pp. 23-24.

[18] Seppä, A.S. Oja, and M. Suhonen, "Micromechanical AC and DC Voltage Reference System," W.O. Patent, PCT/FI99/00553, WO 00/02 110, 1999.

[19] Seppä, J. Kyynäräinen, and A.S. Oja, "Microelectromechanical systems in electrical metrology," IEEE Trans. Instrum. Meas., Vol. 50, No. 2, pp. 440-444, Apr. 2001.

[20] Kärkkäinen, A.S. Oja, J. Kyynäräinen, H. Kuisma, and H. Seppä, "Stability of electrostatic actuation of MEMS," Physica Scripta T, Vol. T, pp. 193-194, 2004.

[21] Wang K and Nguyen C T-C (1999). High-order medium frequency micromechanical filters J. Microelectromech. Syst. **8** 534-57.

[22] Han K-H and Cho Y-H 2003 Self-balanced navigation-grade capacitive microaccelerometers using branched finger electrodes and their performance for varying sense voltage and pressure J. Microelectromech. Syst. **12** 11-20.

[23] Nordholt J E, Young D T and Funsten H O (2000). Plasma experiment for planetary exploration (PEPE) on DS1 IEEE Aerospace Conference Proceedings, Vol 7, pp. 597-607.

[24] Larangot B, Conedera V, Dureuil P, Do Conto T and Rossi C (2002). Solid propellant microthruster: an alternative propulsion device for nanosatellite Aerospace Energetic Equipment Conference (Avignon, France).

[25] “Automatic detection of lung cancer nodules by employing intelligent fuzzy cmeans and support vector machine”, Biomedical Research, August 2016 Impact Factor : 0.226 (SCI, Scopus indexed).

[26] “Cognitive Computational Semantic for high resolution image interpretation using artificial neural network”, Biomedical Research, August 2016 Impact Factor : 0.226(SCI, Scopus indexed).

[27] Noworolski J M and Sanders S R (1998). Microresonant devices for power conversion Proc. SPIE Conf. on Micromachined Devices and Components Vol. 3514, pp. 260-5.