Features

MEMS Based Low Power Efficient Capacitive Inverter for renewable energy applications

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Abstract – In this paper, a micron sized DC/AC power inverter design based on MEMS (micro electromechanical system) is proposed, modeled and demonstrated. The proposed approach uses electrostatic actuation to provide in phase overlap length varying DC/AC inverter system for solar cell application. Two MEMS structures are considered to show good electrical and mechanical performance with zero harmonics and negligible power loss. Also, the actuation voltage is provided under pull in voltage to the actuating part, so that maximum displacement of overlap length is acquired with less instability. The proposed micro scale system exhibits miniaturized volume and expected to acquire improved performance of DC/AC power inverter used for renewable energy applications.

1. Introduction

Power inverters are one of the major concerns to be taken care of, in most of the alternative energy systems for the conversion of DC which is obtained from photovoltaic generators into AC. Several researches are going on these days to improve the efficiency of these high rated power inverters [1]. In semiconductor industries, conventional high rated power inverters based on Si power semiconductor device (PSD)are facilitated [2-3].But, it has several demerits like On-state loss, switching loss of power devices, complex control system configurations, low efficiency, high costs and all these demerits are partially eliminated by PWM Multilevel inverters [4-5].Even then major challenges are present towards large number of switches to be controlled in multilevel power inverter that causes complexity, presence of harmonics that causes high leakage current and also many more deficiencies strongly affect the DC/AC conversion quality performance. On the other hand, MEMS Inverter approach was proposed as an alternative [6-7]. As the micromachining technology that had emerged in the late 1980s [8]. There are wider application fields of MEMS technology like as, RF-MEMS [9-13], biomedical [14], Aerodynamics [15], thermodynamics [16], telecommunication [17] and so on. It is the well-established technology that provides the low power-actuation, low- cost production and miniaturized volume devices [18-20]. Electrostatic principle is the one that is the most important principle among piezoelectric, electromagnetic and electrostatic principles for the MEMS technology [21].

In this paper, the goal is to demonstrate an implementation of proposed design and mathematical modelling of electromechanical DC/AC inverter system of micron size. The proposed MEMS design is based on comb drive structure for the formation of two sets of variable capacitor (driver and converter). One with two sets of electrodes where one is moving (makes the capacitor variable by to and fro movement) and other is fixed. Moreover, the electrostatic actuation is accomplished by external electrical AC signal to the driving capacitor, thereby enabling variation of overlap length of the converter capacitor for the conversion of solar DC input to AC output. The proposed design is simulated in COMSOL 5.0 to see the resulting mechanical movement of electrodes. On the basis of the design, mathematical expressions are modelled using MATLAB 2013for suitable desired electrical performance.

2. Physical modelling of system design

The design consists of fixed comb electrodes (fixed on anchors), moving comb electrodes, a proof mass (substrate) suspended by double folded flexure (having beams, trusses and anchors) beams and a shuttle mass through which moving comb finger electrodes set attached to the substrate (moving mass) as shown in Figure 1. In this design two capacitive sets formed, exhibit in-phase deflection of overlap lengths when subjected to mechanical movement of moving electrodes

which actually means when the capacitance of one set is increased, the other set of capacitance is also increased. And this deflection makes the capacitors variable in nature where one set of capacitors is working as driving part and other set as converter part of the system.

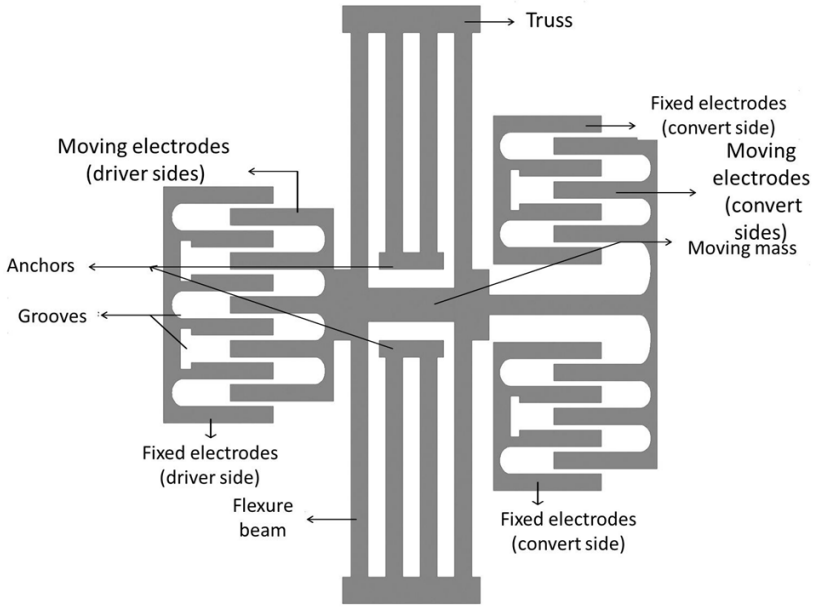

Figure 1: Schematic View of System Design of MEMS Power Inverter.

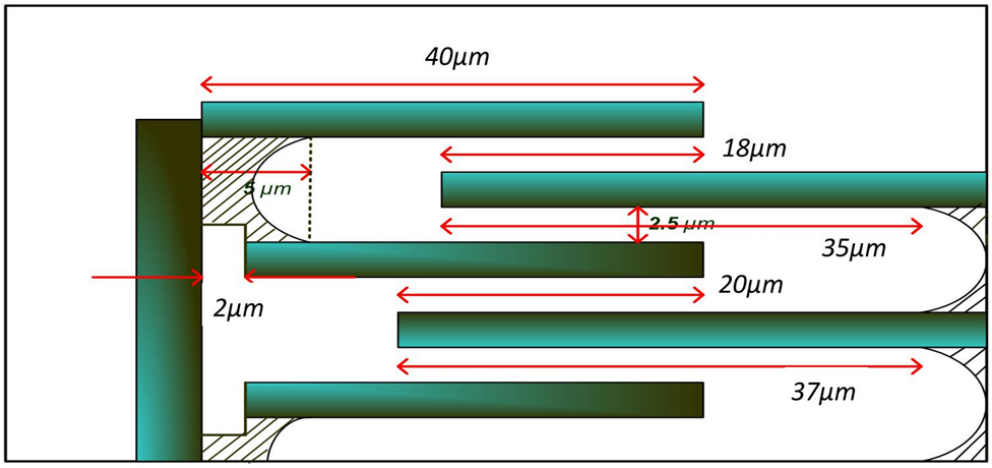

Figure 2: A small part of proposed Interdigitated Capacitor Design (ICD).

The sketch of a small part of the design of comb structure proposed is shown in Figure 2. In the capacitive portion, one moving finger is kept smaller and the next finger of it is kept 1 to 2 µm larger than the previous finger expecting to reduce the fringing effect and to acquire more capacitance formation than the previous work [22].Also, the proposed design consists of groove shaped structure expecting to reduce the front instability of front part of electrodes as because when the actuation is done, not a single pair of capacitor is formed but more than one capacitance is formed [23]. To lessen the effect of the other pair of capacitors, all these changes in capacitor geometry have been done. Thus sample of the proposed design is implemented by using optimization method (using COMSOL 5.0) in which the comb structure (consisting of moving and fixed limbs) is attached to the double folded flexure [24] spring through the moving mass. The detailed specification of the design and the basic materials used are depicted based on the references [25, 26].

3. Operating principle and mathematical representation of MEMS comb structure

The specifications of inputs are provided in Table 1. The equivalent electrical circuit diagram of the proposed system is shown in the Figure 3.

Table 1 Specifications of the input provided to the system designed

INPUT	VALUES
Reference DC Voltage	23.3 V
Reference AC Perturbed voltage	220 V
Frequency	50- 60 Hz (Range)
Solar DC input	24 V
Load(resistive)	10 KΩ

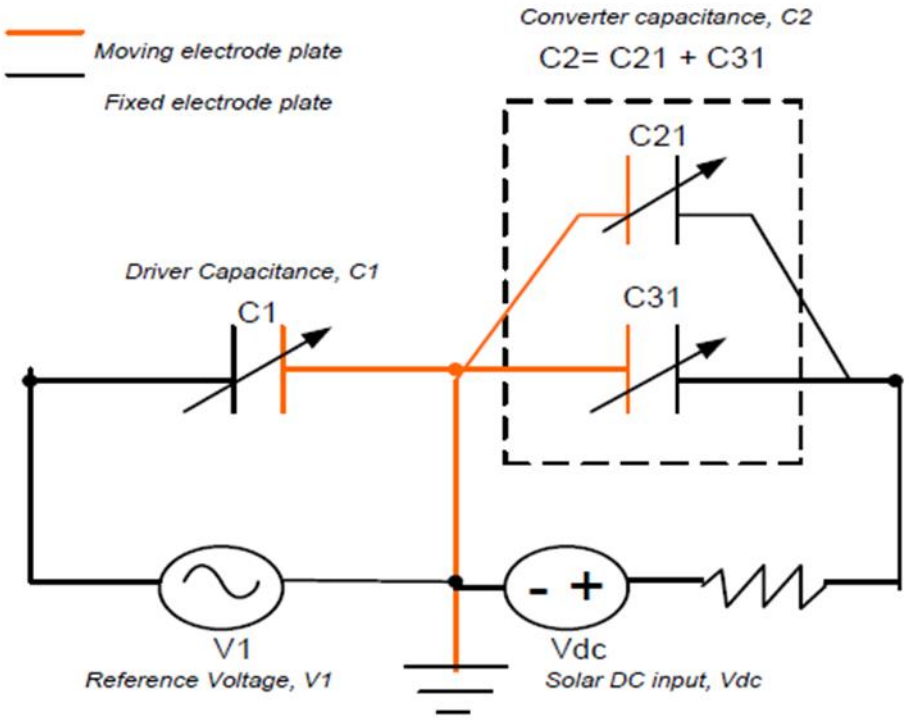

Figure 3: Equivalent Circuit Diagram of MEMS Power Inverter.

Actuating voltage applied on the driving comb structures results in a deflection of the moving fingers in both X and Y directions, but it is preferably in desired Y direction with a small deflection in undesired X-direction because of presence of double folded flexure [22]. The capacitance depends on the geometry of capacitor, not on the applied actuation voltage or accumulated charge. Hence this deflection causes change in overlapping length (l_0) and thus the area changes which finally results in variation of capacitance (C_{var} *(t)*) expressed as equation (1).

$$C = \frac{\varepsilon_0 \varepsilon_r N_e \left(L_0 + \overline{X}\right) t_e}{g} \qquad (1)$$

where ε_0 = Permittivity of vacuum (8.854 × 10^{-12} F/m), ε_r =Medium dielectric constant (1 for vacuum), N_e = Number of movable capacitor's electrodes, L_0 = Electrode's initial overlapping length, t_e = Electrode's thickness, g = The gap between movable and fixed electrodes. An equal and opposite charges build on the surface of electrodes due to the potential difference between the electrodes (fixed and moving) because of which electrostatic force (F_{es}) developed in between the electrodes is

$$F_{es} = \frac{1}{2}\left(\frac{dC_{\text{var}}(t)}{dy}\right)V^2 = \frac{1}{2}\left[\left(\frac{dC_1(t)}{dy}\right)V_1^2 + \left(\frac{dC_2(t)}{dy}\right)V_{2\text{var}}^2(t)\right] \qquad (2)$$

Where, $C_1(t)$ =Driving capacitance, $C_2(t)$ =Equivalent converter capacitance in which the two sets of capacitor are connected in parallel shown in the Figure 4 is

$C_2(t) = C_{2i} + C_{3j}$ (3)
i, j=1,2,3....N_e

$$\frac{dC_{\text{var}}(t)}{dy} = \begin{Bmatrix} \frac{C_0}{I_0}, \bar{y} = y \\ \frac{-C_0}{I_0}, \bar{y} = y \end{Bmatrix}$$, Rate of change of capacitance with displacement

Where $V_1 =$ Driving voltage or reference voltage

$$V_1 = \sqrt{\left(V_{AC}^{\ 2}\right) + \left(V_{1DC}^{\ 2}\right)} \quad (4)$$

Where, V_{1DC} = Reference DC bias Voltage, V_{AC} = AC perturbed reference voltage. V_1 can be varied so as to change the amount of charge (Q_{c1}) accumulated on the surface of electrodes and moving electrodes allow the use of that charge ($Q_{c2}(t)$) as an intermediate variable which can be used to control the change in l_0 so that $C_2(t)$ is increased and voltage ($V_{2\text{var}}(t)$) across $C_2(t)$

$$V_{2\text{var}}(t) = \frac{1}{c_2(t)} \int i_{\text{var}}(t) \partial t \quad (5)$$

By applying KVL in the electrical domain of converter side, the resulting relation is –

$$V_{2\text{var}}(t) = V_{DC} - R_L i_{\text{var}}(t) \quad (6)$$

Where V_{DC} =Solar DC input voltage , R_L =Load Resistance, $i_{Var}(t)$ =Current in the converter circuit

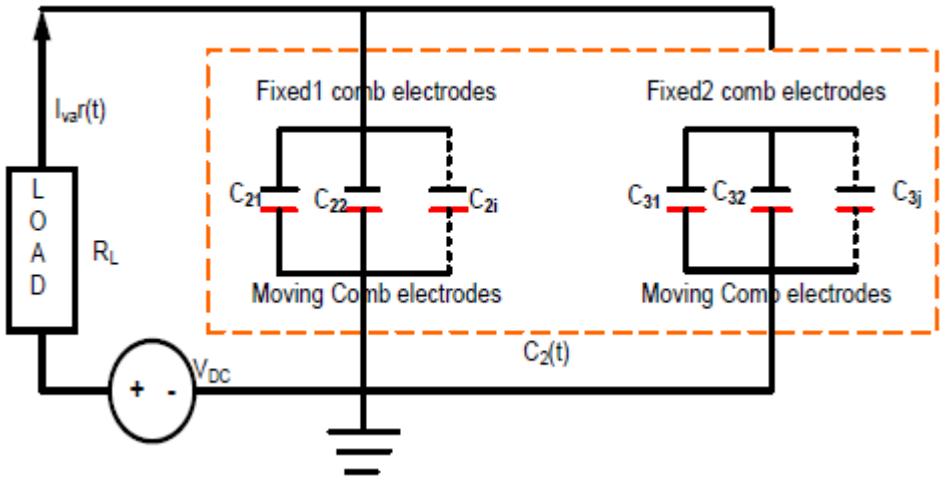

Figure 4: Converter Circuit Diagram in Electrical Domain.

$$i_{\text{var}}(t) = \frac{dQ_{c2}(t)}{dt} = \frac{d}{dt}\left[C_2(t) V_{2\text{var}}(t)\right]$$

$$i_{\text{var}}(t) = V_{2\,\text{var}}(t)\left[\frac{dC_2(t)}{dt}\right] + C_2(t)\left[\frac{dv_{2\,\text{var}}(t)}{dt}\right]$$

$$V_{DC} - \left\{\frac{C_2(t)R_L\left[\frac{di_{\text{var}}(t)}{dt}\right]}{\frac{dC_2(t)}{dt}}\right\} - \left\{R_L + \frac{1}{\frac{dC_2(t)}{dt}}\right\} i_{\text{var}}(t) = 0$$

$$V_{DC} - L_2(t)\left[\frac{di_{\text{var}}(t)}{dt}\right] - \{R_L + R_2(t)\} i_{\text{var}}(t) = 0 \qquad (7)$$

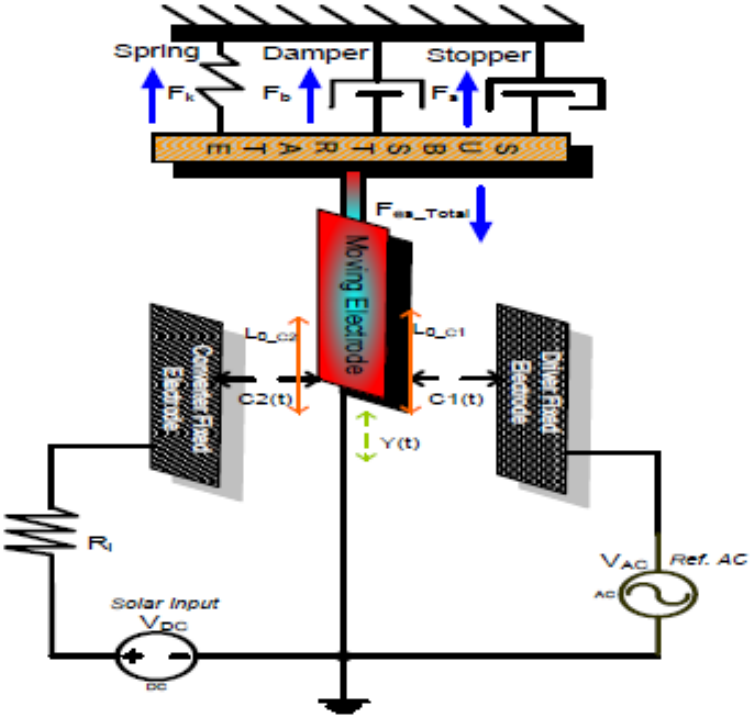

Figure 5: Simplified Circuit Diagram of the proposed MEMS inverter.

The equation **(7)** represents the converter circuit consists of source V_{DC} in series with [varying inductor $L_2(t)$) and varying resistor ($R_2(t)$) as new components [18] of] $C_2(t)$ and R_L

$$R_2(t) = \left[\frac{1}{\frac{dC_2(t)}{dt}}\right] \qquad (8)$$

$$L_2(t) = \left[\frac{R_L C_2(t)}{\frac{dC_2(t)}{dt}}\right] \qquad (9)$$

Where, inductive part (9) represents the energy storage element results from coupling between the capacitor converter circuit and the load resistance. Resistive part (8) represents the open circuit resistance meant for the measure of energy dissipation i.e. for minimum internal resistance; we require increment in the value of rate of change of capacitance. Continuously growing of electrostatic force causes the displacement in positive Y-direction. In order to keep the electrodes away from 'esp of bursting', an equal and opposite force resisting this motion is modeled by restoring force [27-29] of a mechanical spring with spring constant (k) and a damper with damping coefficient (b_m). The total force acting on the system design is shown in the Figure 5.

The balance force is defined as equation 10.

$$my + b_m y + ky + F_s = mA_{es} + F_{es} \quad (10)$$

The term, mechanical stopper force (F_s) is the resultant mechanical force used to limit the deflection of moving mass by

$$F_s = \begin{Bmatrix} 0, & -y_s \le y \le y_s \\ k_s(y + y_s), & y < -y_s \\ k_s(y - y_s), & y > y_s \end{Bmatrix}$$

Where, k_S =Stiffness constant of stopper $\pm y_S$ = Moving mass deflection limit.

4. Results and discussion

Mathematical modeling of the proposed MEMS power inverter is simulated using MATLAB Simulink to determine the resulting plots of converted AC voltage and force versus displacement shown in the Fig 6. It is observed from the plots that converted AC voltage obtained is of amplitude 4.7V across the Load (10 KΩ) at the solar input of 19.6V when the system is being actuated by reference of 130V, 50 Hz; AC and 3V; DC bias voltage for 2 seconds. The electrostatic force built up to 16.6× 10^-4 N which facilitates the maximum displacement of overlap length up to 9 µm.

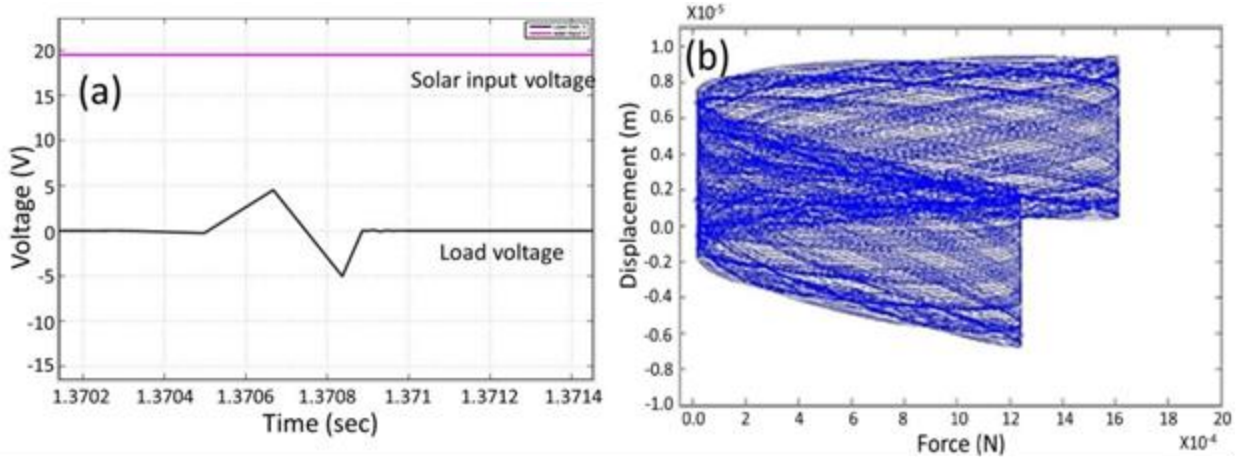

Figure 6: Converted Voltage across Load with Solar Input Voltage Versus time Plot, (b) Force Built up Versus Displacement Plot

For the concept demonstration and the comparison purposes, only a half part of the proposed design is simulated in COMSOL 5.0 Multiphysics taking two cases (a) simple rectangular and (b) modified rectangular grooved comb drive structure. Comparisons of two different cases (models) are done on the basis of the following parameters like electric potential distribution, displacement and capacitance variation. The resulting surface plot of electric potential distribution and the displacement facilitated by actuation voltage of 23.3V for both the models. Also, the displacement and capacitance variation with respect to the applied voltage can be seen and measured clearly from Fig.7.

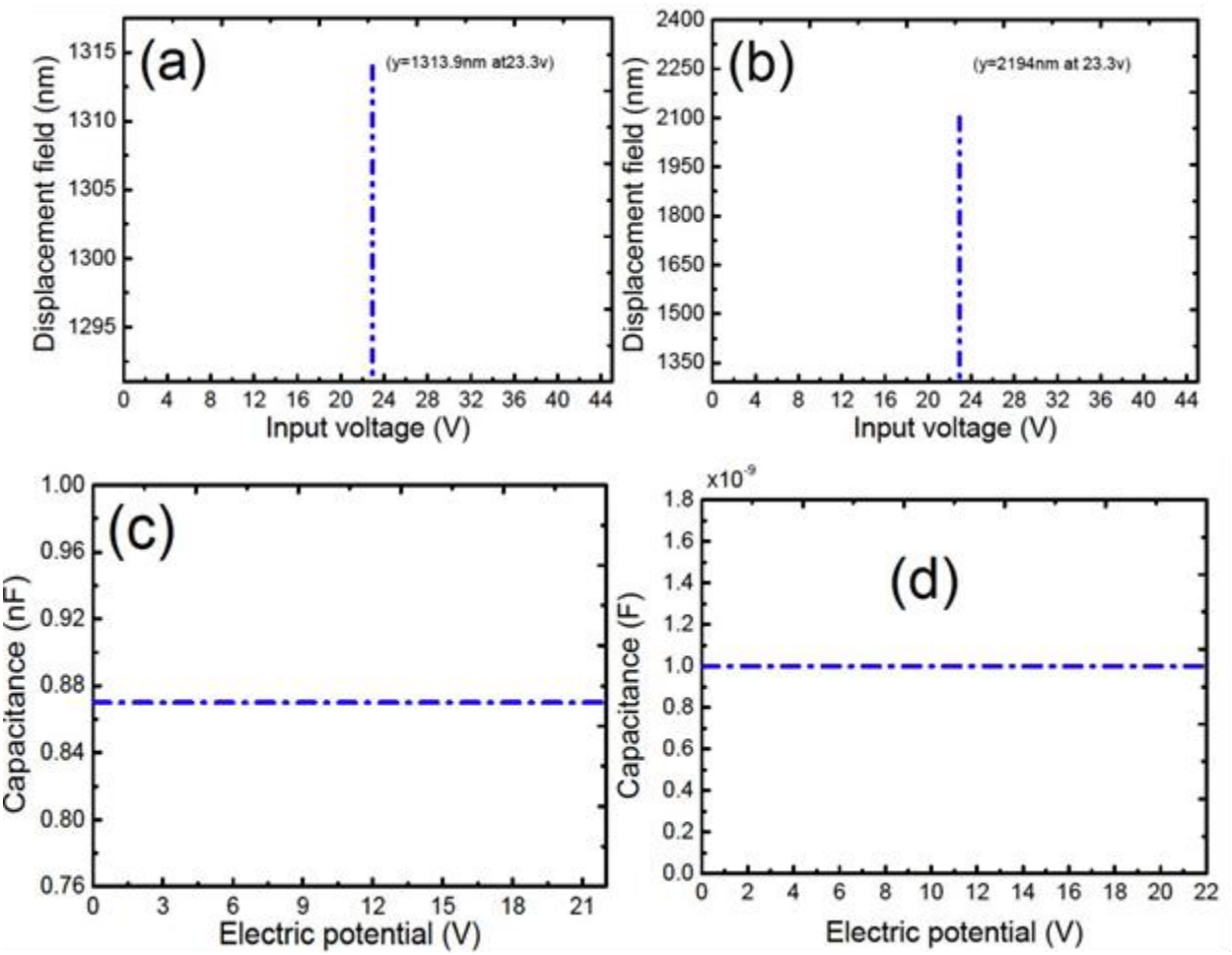

Figure 7: (a), (b) Displacement(y) Vs applied Voltage for both the models (1 & 2), (c)(d) Capacitance(C) Vs. Electric Potential for both the models (1 & 2) (C=0.8701nFC=0.9623 n)

Table 2 Resulting Values of Plot 7

DESCRIPTION	INPUT VOLTAGE	MAXIMUM DISPLACEMENT	CAPACITANCE VALUE
Model 1	23.3 V	(1289.7-1313.9) nm	0.8701 nF
Model 2	23.3 V	(2189.6-2194) nm	0.9623 nF

It is seen in figure 7 that the displacement and capacitance values of case I are more than case 2 (table 2). Actuation depends on the number of comb fingers [24] which is related to electrostatic force and capacitance. Surface electric potential and displacement plot of the moving electrodes are observed so that the capacitance formed due to the fixed and moving electrodes are being varied and the graphs are obtained and shown in the figure 8. Displacement shown in the fig. 8 (b) is towards the Y-direction that actually meant for the enhancement of the overlap length of the capacitors because of which the overlapping area increases. The increase in overlapping area facilitates the increase of capacitance across the converter circuit.

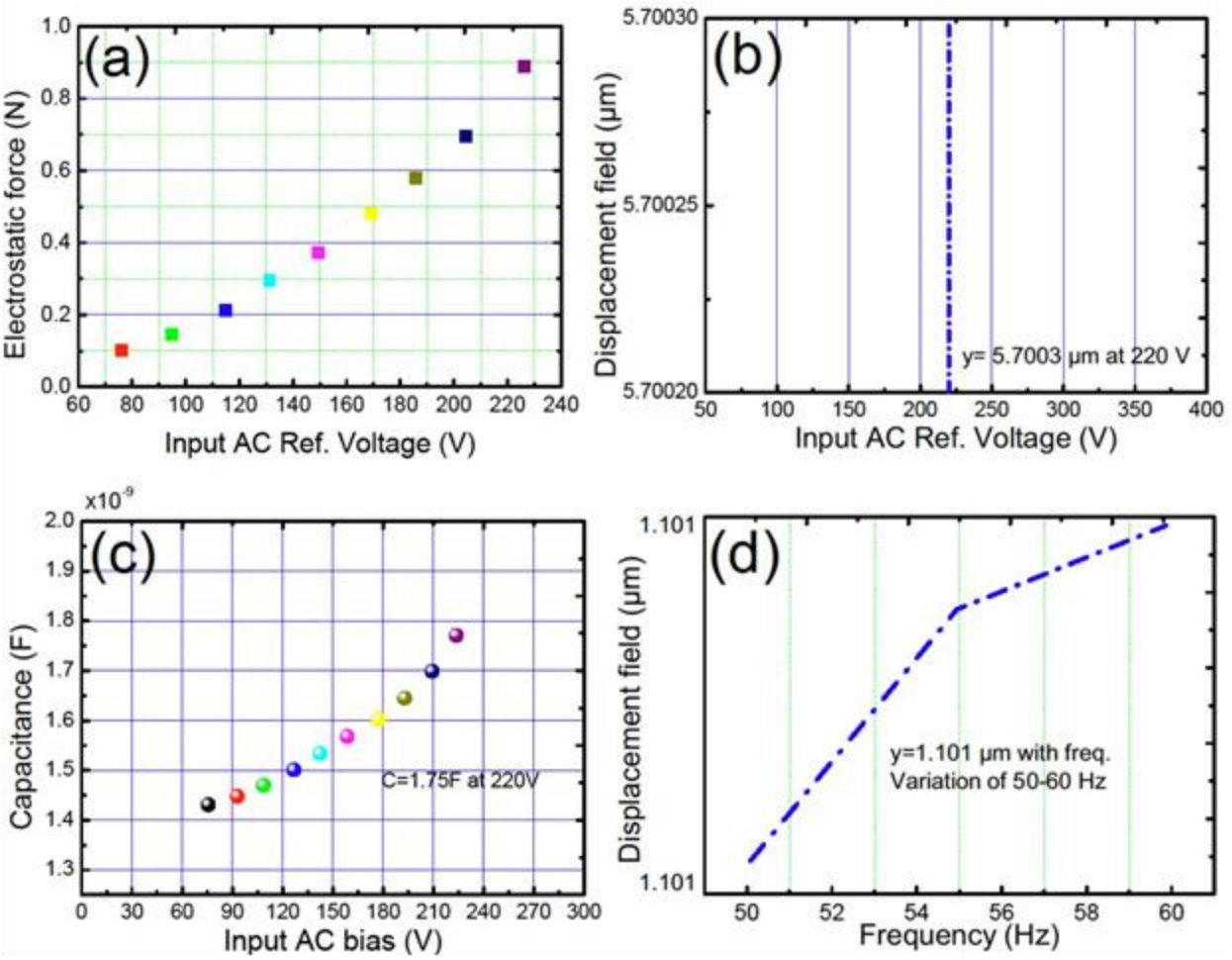

Figure 8: (a) Electrostatic force (F) Vs Reference Voltage (F= 0.84 N at 220 V), (b) Displacement (y) Vs Actuation Voltage (V), (c) Capacitance (C) Vs Actuation Voltage, (d) Displacement (y) versus Frequency (f) (Hz).

From the plots in Figure 8, it is seen that due to the actuation voltage, the electrostatic force is built up in between the two electrodes (fixed and moving) which is proportional to the square of the applied voltage and its variation with different values of voltage is shown by the plot 8(a). The electrostatic force further causes the displacement in overlap length which then induces change in capacitance and as the capacitance is inversely proportional to the voltage; here its variation with voltage is shown in Fig. 8(c). Also, the displacement depends on the frequency of the AC perturbed reference voltage which can be clearly shown by the plot (d) of Figure 8. Low power VLSI application is major concert in the current technology [30, 31]. The proposed model is applicable for low cost and low power application.

5. Conclusion

This paper proposed a solution to the critical problem of DC/AC conversion quality performance of commercial power inverter used for renewable energy applications by adopting the MEMS based capacitive power inverter system. Owing to the proposed concept, mechanical part of the system is designed to have a high level of stiffness in order to be actuated by the power grid voltage. The proposed MEMS approach enables the non-complexity of the inverter, zero harmonics, miniaturized volume device, low cost production and very less losses (almost lossless). It also doesn't consume power for the DC/AC conversion process. It is developed in this work by means of simulations of two models for comparison and the modified comb drive design is proposed so as to lessen the instabilities with acquisition of more capacitance formation across interdigitated electrodes so that it can be directly used in MEMS capacitive Transducer.

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